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THE JOURNAL OF

The Institution of Electrical Engineers

ORIGINALLY

The Society of Telegraph Engineers

VICTORIA EMBANKMENT, LONDON, W.C. 2.

TEMPORARY OFFICES: 1, ALBEMARLE STREET, LONDON, W. 1.

FOUNDED 1871

"TO PROMOTE THE GENERAL ADVANCEMENT OF ELECTRICAL AND TELEGRAPHIC SCIENCE AND ITS APPLICATIONS."

EDITED BY P. F. ROWELL, SECRETARY.

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The Institution of Electrical Engineers.

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TEMPORARY OFFICES : 1, ALBEMARLE STREET, LONDON, W. 1.

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(Corrected 1st January, 1920.)

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The Institution is not, as a body, responsible for the opinions expressed by individual authors or speakers.

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CORRIGENDA.

Vol. 58, p. 11, col. 2, lines 23 to 29 should read:

Total Use of Electricity by 7 British Railways for Traction, Lighting and Power, including Actual Commitments to have been carried out but for the War.

Electricity generated and bought by 7 railways, kw.-hours	640,271,920
Maximum one-hour demand, kw.d.	196,250
Annual one-hour load factor, per cent	37·3

Vol. 58, p. 141, Table: *Delete* "16,986 1914 Siemens Bros. Dynamo Works & E. O. Kieffer Liquid-cooled rotors."

THE INSTITUTION OF ELECTRICAL ENGINEERS.

No. 16. DECEMBER 1919. INSTITUTION NOTES. [ISSUED WITH No. 286 OF THE JOURNAL.]

Arrangements for December 1919 and January 1920.

ORDINARY MEETINGS OF THE INSTITUTION.

[To be held at the Institution of Civil Engineers, Great George-street, Westminster, S.W., at 6 p.m. (light refreshments 5.30 p.m.).]

Date.	*Author and Title of Paper.*
1919.	
11 Dec.	J. M. SCOTT-MAXWELL : "Scientific Management."
18 Dec.	D. M. W. HUTCHISON and W. J. WAYTE : "Electricity in Tin Mining."
1920.	
8 Jan.	J. SHEPHERD : "Failures of Turbo-Generators and Suggestions for Improvements."
22 Jan.	J. L. THOMPSON, M.Sc. : "Transformers for Electric Furnaces."

WIRELESS SECTIONAL MEETING.

[To be held at the Institution of Civil Engineers, Great George-street, Westminster, S.W., at 6 p.m. (light refreshments 5.30 p.m.).]

Wednesday, 17 Dec.	Professor G. W. O. HOWE, D.Sc. : "The High-frequency Resistance of Wires and Coils."

INFORMAL MEETINGS.

[To be held in the lecture-hall of the Chartered Institute of Patent Agents, Staple Inn Buildings (South Block), W.C.]

1919.	
Monday, 15 Dec. (7 p.m.)	Discussion on "Some Reflections on Labour" (Introduced by Mr. R. Rankin).
1920.	
Monday, 19 Jan. (7 p.m.)	Discussion on "Functions of a Trade Journal" (Introduced by Mr. S. M. HILLS).

MEETINGS OF TERRITORIAL CENTRES.

Date.	*Place of Meeting.*	*Author and Title of Paper.*
1919.		
1 Dec.	Bristol	Address by Mr. W. A. CHAMEN.
2 Dec.	Manchester	Discussion on "Electricity Supply."
3 Dec.	Birmingham	G. L. ADDENBROOKE : "Dielectrics in Electric Fields" (Lecture).
4 Dec.	Preston	W. E. HIGHFIELD and J. E. CALVERLEY : "Overloads on Commutating Machines."
9 Dec.	Bradford	Discussion on "The Linking-up Report."
9 Dec.	Glasgow	J. M. SCOTT-MAXWELL : "Scientific Management."
15 Dec.	Newcastle	J. LYTHGOE : "Electrical Developments at Christchurch, New Zealand" (Lecture).
16 Dec.	Manchester	J. M. SCOTT-MAXWELL : "Scientific Management."
17 Dec.	Birmingham	J. M. SCOTT-MAXWELL : "Scientific Management."
18 Dec.	Dublin	T. C. ROBERTS : "Water Power."
1920.		
6 Jan.	Preston	H. E. O'BRIEN, D.S.O. : "Electric Traction."
12 Jan.	Newcastle	J. M. SCOTT-MAXWELL : "Scientific Management."
13 Jan.	Edinburgh	(To be announced later.)
13 Jan.	Leeds	A. G. ELLIS and J. L. THOMPSON : "Large Power Transformers."
13 Jan.	Manchester	(To be announced later.)
14 Jan.	Birmingham	H. W. TAYLOR : "Eddy Current Losses in Stator Windings."
15 Jan.	Birmingham	Joint Meeting with Midland Junior Gas Association.
19 Jan.	Liverpool	Address by Prof. E. W. MARCHANT, D.Sc. (Inaugural Meeting of Liverpool Sub-Centre.)
26 Jan.	Newcastle	J. SHEPHERD : "Failures of Turbo-Generators and Suggestions for Improvements."
27 Jan.	Manchester	(To be announced later.)
28 Jan.	Birmingham	J. SHEPHERD : "Failures of Turbo-Generators and Suggestions for Improvements."
30 Jan.	Newcastle	Annual Dinner of North-Eastern Centre.

STUDENTS' SECTION.

MEETINGS.

Date.	*Place and Time of Meeting.*	*Author and Title of Paper.*
1919.		
5 Dec.	City and Guilds Technical College, Finsbury, E.C. (7 p.m.)	H. M. BARLOW : "Thermionic Magnifiers."
1920.		
16 Jan.	City and Guilds Engineering College, South Kensington, S.W. (7 p.m.)	J. H. REYNER : "The Development of Automatic Telephony."

STUDENTS' VISITS TO WORKS.

Date.	*Time.*	*Works to be Visited.*
1919.		
12 Dec.	2 p.m.	The Royal Arsenal, Woolwich.
1920.		
30 Jan.	2 p.m.	Streatham Common Rubber Works and East Surrey Iron Works.

The above visits, for which tickets of admission are necessary, are open only to Students of the Institution, and those wishing to attend should notify Mr. H. T. Body, 54, Chadwick-road, Leytonstone, E. 11, at least 10 days before each visit. In some cases the number forming the party is limited by the authorities of the works to be visited, and on these occasions the Committee will decide by ballot or otherwise which Students may attend.

SMOKING CONCERT.

A Smoking Concert will be held at the Ship Restaurant, 45, Charing Cross, W.C., on Friday, 19th December, at 7.30 p.m. Tickets, to include refreshments, can be obtained from Mr. H. T. Body, 54, Chadwick-road, Leytonstone, E. 11, price 3s. 6d. each.

Irish Centre (Belfast).

The following have been appointed to be a Preliminary Committee to take the necessary steps to inaugurate the Irish Centre (Belfast) :—

Mr. T. W. Bloxam.
Mr. E. S. Dashwood.
Mr. R. V. Macrory.
Mr. F. W. Parkinson.
Prof. R. Stanley (*Acting Hon. Secretary*).
Mr. H. D. Wight.

Scholarships.

The Council have awarded the following Scholarships for 1919–20 :—

Salomons Scholarships (value £50 each) to Mr. J. C. Read, of Bristol University, and to Mr. H. J. Barriscale, of the Engineering School, University College, Cork.

David Hughes Scholarships (value £50 each) to Mr. D. S. Anderson, of the Royal Technical College, Glasgow, and to Mr. B. A. Cronin, of the University College of South Wales and Monmouthshire.

Paul Scholarship (value £25) to Mr. F. E. Price, of the Finsbury Technical College.

Students' Section.

Mr. G. W. Partridge has been re-appointed to be the Member of Council to act as a consultative member of the Students' Committee for the present session (see *Institution Notes*, No. 11, February, 1919, p. 18).

The Institution of Engineers (India).

The Council have decided to award, for the next five years, an annual prize of £20 for the best paper on an electrical subject read before the above Institution.

Informal Meeting.

The fifth Informal Meeting was held on Monday, 17th November, 1919, at 7 p.m., at the Chartered Institute of Patent Agents, Staple Inn Buildings, W.C., Mr. Roger T. Smith, President, in the chair.

After an opening statement by the Chairman, inviting members to offer introductory papers for future meetings, Mr. W. E. Warrilow opened a discussion on "Engineering Advertising," and in the discussion which followed Messrs. O. Pearston, J. F. Avila, R. Rankin, R. W. Hughman, W. A. Moore, — Mahoney, J. W. Beauchamp, J. Eck, A. B. Eason, T. C. Elder, A. F. Harmer, — Fisher, and — McCallum spoke.

Committees, 1919–1920.

Among the Committees appointed by the Council for 1919–20 are the following :—

INFORMAL MEETINGS.

The President.

Mr. W. E. Bradshaw.
Dr. R. D. Gifford.
Mr. A. F. Harmer.
Mr. S. M. Hills.
Mr. G. C. Law.
Mr. F. Pooley.
Mr. R. Rankin.
Mr. W. E. Warrilow.
Mr. C. H. Wordingham, C.B.E.
Mr. W. L. Wreford.

LIBRARY AND MUSEUM.

The President.

Mr. D. N. Dunlop.
Mr. K. Hedges.
Mr. W. M. Mordey.
Lt.-Col. W. A. J. O'Meara, R.E., C.M.G.
Mr. C. C. Paterson, O.B.E.
Mr. A. P. Trotter.

"SCIENCE ABSTRACTS."

The President.

Mr. J. Devonshire.
Prof. E. W. Marchant, D.Sc.
Mr. W. M. Mordey.
Mr. C. C. Paterson, O.B.E.

And	*Representing*
Mr. W. R. Cooper Prof. J. W. Nicholson	The Physical Society of London.

SHIP ELECTRICAL EQUIPMENT.

The President.

Mr. J. H. Collie.
Mr. B. M. Drake.
Mr. A. Henderson.
Mr. J. W. Kempster.
Mr. J. F. Nielson.
Mr. N. W. Prangnell.
Mr. A. P. Pyne.
Mr. T. A. Sedgwick.
Mr. S. G. C. Russell.
Mr. C. H. Wordingham, C.B.E.

And	*Representing*
Mr. W. S. Abell Mr. J. T. Milton	Lloyd's Register of Shipping.
Mr. H. H. Berry Mr. C. Rodgers	British Electrical and Allied Manufacturers' Association.
Mr. T. Carlton	Board of Trade.
Mr. W. Cross	Electrical Contractors' Association.
Mr. J. Foster King	British Corporation for the Survey and Registry of Shipping.
Mr. J. Lowson	Institution of Engineers and Shipbuilders in Scotland. Electrical Contractors' Association of Scotland.
Mr. A. W. Stewart	Institution of Naval Architects.
Mr. H. Walker, O.B.E.	N.E. Coast Institution of Engineers and Shipbuilders.

TERRITORIAL CENTRES.

The President.

Mr. H. J. Cash.
Mr. W. A. Chamen.
Mr. J. Devonshire.
Mr. D. N. Dunlop.
Mr. G. W. Partridge.
Mr. W. B. Woodhouse.
Mr. C. H. Wordingham, C.B.E.,

and the Chairman of each Territorial Centre.

WIRELESS SECTIONAL MEETINGS.

The President.

Major E. A. Barker, M.C.
Sir Charles Bright, F.R.S.E.
Dr. W. H. Eccles.
Squadron Leader J. Erskine-Murray, R.A.F.
Mr. Andrew Gray.
Prof. G. W. O. Howe, D.Sc.
Admiral Sir H. B. Jackson, G.C.B., K.C.V.O., F.R.S.
Mr. W. Judd.
Sir Oliver Lodge, D.Sc., F.R.S.
Prof. E. W. Marchant, D.Sc.
Dr. G. Marconi, G.C.V.O., LL.D.
Captain H. R. Sankey, C.B., R.E. (ret.).
Mr. J. Sayers.
Major T. Vincent Smith, R.A.F.
Mr. A. A. C. Swinton, F.R.S.
Mr. J. E. Taylor.
Mr. C. H. Wordingham, C.B.E.

And	*Representing*
Lt.-Col. W. L. Evans, C.M.G., D.S.O., R.E. ..	War Office.
Mr. E. H. Shaughnessy, O.B.E.	Post Office.
Capt. J. K. Im Thurn, R.N.	Admiralty.
Lt.-Col. A. D. Warrington-Morris, C.M.G., O.B.E. ..	Air Ministry.

WIRING RULES.

The President.

Mr. Ll. B. Atkinson.
Mr. R. H. Campion.
Mr. H. J. Cash.
Mr. J. R. Cowie.
Mr. W. Cross.
Mr. J. F. Nielson.
Mr. A. P. Pyne.
Mr. C. H. Wordingham, C.B.E.
Mr. J. Frith.
Mr. S. W. Melsom.

And	*Representing*
Mr. B. M. Drake ..	Contractors (unofficially).
Sir T. O. Callender .. / Mr. J. F. W. Hooper ..	Cable Makers (unofficially)
Mr. S. G. C. Russell .. / Mr. A. L. Taylor ..	Fire Offices (unofficially).
Mr. H. H. Berry .. / Mr. J. R. Dick	The British Electrical and Allied Manufacturers' Association.
Mr. W. E. Gray	The Cable Makers' Association.
Mr. E. J. B. Lowdon ..	The Electrical Contractors' Association of Scotland.
Mr. J. Christie .. .. / (One vacancy) ..	The Incorporated Municipal Electrical Association.
Mr. E. T. Ruthven-Murray	The Incorporated Association of Electric Power Companies.
Mr. W. R. Rawlings .. / Mr. S. H. Webb ..	The Electrical Contractors' Association.
Mr. J. M. Crowdy ..	The National Association of Supervising Electricians.
Mr. C. P. Sparks ..	Conference of Chief Officials of the London Electric Supply Companies.

SECTIONAL COMMITTEES.

Lighting and Power.

The President.

Mr. H. W. Clothier.
Mr. J. S. Highfield.
Mr. G. W. Partridge.
Mr. C. P. Sparks.
Mr. B. Welbourn.
Mr. W. B. Woodhouse,
and 3 non-members of Council to be co-opted by the Committee.

Electricity in Mines.

The President.

Mr. W. A. Chamen.
Mr. H. W. Clothier.
Mr. W. B. Hird.
Mr. W. C. Mountain
Mr. R. Nelson.
Mr. W. H. Patchell.
Mr. W. M. Selvey.
Mr. C. P. Sparks.
Mr. W. B. Woodhouse.

Traction.

The President.

Lt.-Col. F. A. Cortez-Leigh.
Mr. J. Devonshire.
Mr. A. Ellis.
Mr. H. W. Firth.
Mr. F. Lydall.
Mr. A. H. W. Marshall.
Mr. G. W. Partridge.
Mr. J. Sayers.
Mr. B. Welbourn.

Electro-Chemistry and Electro-Metallurgy.

The President.

Mr. S. E. Fedden.
Sir R. A. Hadfield, Bart., F.R.S.
Mr. J. S. Highfield.
Mr. W. M. Mordey.
Mr. C. P. Sparks.
Mr. J. Swinburne, F.R.S.,
and 3 non-members of Council to be co-opted by the Committee.

Telegraphs and Telephones.

The President.

Mr. J. Sayers.
Sir Charles Bright, F.R.S.E.
Mr. H. G Brown.
Mr. F. Gill.
Mr. H. H. Harrison.
Mr. W. Judd.
Mr. W. Noble.
Mr. F. Ryan.
Sir William Slingo.

Representatives of The Institution on Other Bodies.

The following is a list of representatives of the Institution on other bodies and the dates on which they were appointed.

Birmingham Chamber of Commerce:

S. T. Allen (27 March, 1919).

Bradford Public Libraries Committee:

Mr. T. Roles (27 Feb., 1919).

Bristol University:

Mr. H. F. Proctor (6 Dec., 1917).

British Engineering Standards Association:

Main Committee:

Col. R. E. Crompton, C.B. (2 April, 1914).
Sir John Snell (2 April, 1914).
Mr. C. P. Sparks (2 April, 1914).

STUDENTS' SECTION *—continued.*

MEETINGS.

Date.	*Author and Title of Paper.*
1920.	
30 Jan.	Discussion on "Quantity Production as a Panacea" (Introduced by Major K. Edgcumbe). (*At Finsbury Technical College, 7 p.m.*)
6 Feb.	F. R. HOUSDEN: "Electric Lifts and Cranes." (*At the City and Guilds Engineering College, South Kensington, 7 p.m.*)
20 Feb.	Discussion on "State Ownership versus Private Enterprise" (Introduced by A. Serner). (*At Faraday House, 7 p.m.*)

STUDENTS' VISITS TO WORKS.

Date.	*Time.*	*Works to be Visited.*
1920.		
28 Jan.	2 p.m.	Streatham Common Rubber Works, and East Surrey Iron Works.
14 Feb.	2 p.m.	Chingford Pumping Station of Metropolitan Water Board.
27 Feb.	2 p.m.	Messrs. Johnson and Phillips' works, Charlton, S.E.

The above visits, for which tickets of admission are necessary, are open only to Students of the Institution, and those wishing to attend should notify Mr. H. T. Body, 54 Chadwick-road, Leytonstone, E. 11, at least 10 days before each visit. In some cases the number forming the party is limited by the authorities of the works to be visited, and on these occasions the Committee will decide by ballot or otherwise which Students may attend.

Annual Dinner.

The Annual Dinner of the Institution will be held at the Connaught Rooms, Great Queen-street, London, W.C., on Thursday, 4th March, at 7 p.m. for 7.30 p.m.

International Illumination Commission.

Mr. Percy Good has been appointed by the Council to be one of the representatives of the Institution on the British National Committee of the above Commission.

Informal Meetings.

The sixth Informal Meeting was held on Monday, 15th December, 1919, at 7 p.m., at the Chartered Institute of Patent Agents, Staple Inn Buildings, W.C., Mr. A. F. Harmer in the chair.

Mr. R. Rankin opened a discussion on "Some Reflections on Labour," in which the following took part: Major T. Rich, R.E., O.B.E., Messrs. R. E. Dickinson, J. W. Beck, Dr. R. D. Gifford, Messrs. A. B. Eason, A. Humphreys, A. C. Wilmot, G. C. Law, F. Pooley, F. H. Masters, O.B.E., and F. N. Haward.

The Chairman announced that it had been decided not to arrange for visits to works during the present session.

The seventh Informal Meeting was held on Monday, 19th January, 1920, at 7 p.m., at the Chartered Institute of Patent Agents, Staple Inn Buildings, W.C., Mr. W. E. Bradshaw in the chair.

Mr. F. H. Masters, O.B.E., opened a discussion on "Functions of a Trade Journal," in which the following took part:—Messrs. F. H. Nalder, W. E. Warrilow, R. Rankin, S. M. Hills, O. Pearston, J. C. Rennie, A. G. Whyte, A. H. Allen, F. Pooley, A. G. Hilling, R. W. Hughman, A. B. Eason, and W. E. Bradshaw.

The Chairman announced that it had been decided to hold an Informal Social Evening on Monday, 29th March, particulars of which will be announced later.

I.E.E. Wiring Rules.

The Council have approved the following recommendation of the Wiring Rules Committee:—

"That Wiring Rule 39 be amended to read as follows:

"39. Except for wiring fittings, the cross-sectional area (Table, Col. 2) of any copper conductor must not be less than 0·0015 square inch (1/·044″). The cross-sectional area of fittings wires must not be less than 0·0010 square inch (1/·036″)."

A complete revision of the Wiring Rules is in hand, and the Committee will be glad to receive suggestions (in the form of specific amendments) for consideration during the revision. Suggestions should be addressed to the Secretary of the Institution, 1, Albemarle Street, London, W. 1. Many valuable suggestions have already been received.

Mr. L. L. Robinson has been nominated by the Incorporated Municipal Electrical Association to serve on the Committee in addition to Mr. J. Christie; and Mr. O. M. Andrews has been nominated by the Conference of Chief Officials of the London Electric Supply Companies as their representative on the Committee in place of Mr. C. P. Sparks, who retired from the Conference on the 31st December, 1919. Mr. Sparks has agreed to serve on the Committee in his private capacity.

International Electrotechnical Commission.

The Secretary of the Institution has received the following for publication :

The Plenary Meeting of the International Electrotechnical Commission was held in London from October 20th to 23rd at the Institution of Civil Engineers.

The British National Committee, of which Sir Richard Glazebrook, K.C.B., is Chairman, is now under the ægis of the British Engineering Standards Association in accordance with the settled policy of the Institution that all standardization should be carried out by the B.E.S.A., and all rules and regulations be prepared by the Institution.

There were over 50 delegates present from 19 countries, and they were received by Monsieur Maurice Leblanc, President of the Commission.

The delegates were welcomed by Sir Richard Glazebrook, K.C.B., President of the British National Committee, Mr. Roger T. Smith, President of the Institution on behalf of the I.E.E. Council, and Mr. A. R. Everest on behalf of the British Electrical and Allied Manufacturers' Association.

A banquet was given to the delegates by the President and Members of the British National Committee, the President and Council of the Institution, and the Chairman and Council of the British Electrical and Allied Manufacturers' Association on Tuesday, 21st October, 1919, at which the Rt. Hon. A. J. Balfour, O.M., gave an Address.

At the Plenary Meeting held on 22nd October, it was unanimously decided to re-appoint the following Advisory Committees (previously known as Special Committees) :—

Nomenclature.
Rating of Electrical Machinery.
Symbols.
Prime Movers for Electrical Plant.

and also to appoint the following additional Advisory Committees :—

Aluminium.
Screw Lamp Caps and Lampholders.
Charging Plugs for Electrical Vehicles.
Standard Pressures for Distribution and Insulators.

It was decided to hold meetings of the Advisory Committees in Brussels in the early spring of 1920, the Central Office being empowered to make the necessary arrangements.

At the meeting of the Council of the Commission held on Wednesday, 22nd October, Dr. Mailloux was unanimously elected as the new President of the Commission. Dr. Mailloux was one of the founders of the Commission and its success has been due, in no small measure, to his efforts on its behalf. His great linguistic abilities have been of the utmost service on many occasions.

The Council accepted the invitation of the United States National Committee to hold the next Plenary Meeting in the United States of America during the summer of 1920.

At the close of the meeting a silver cup, subscribed for by his friends, was presented to Colonel R. E. Crompton, C.B., the Honorary Secretary of the Commission, by Dr. Mailloux.

Accessions to the Reference Library.

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AMÉDÉO, R. Recherches expérimentales sur le coupage des fers et aciers par les chalumeaux à jet d'oxygène. 8vo. 72 pp. *Paris*, 1913

ANDERSON, W. T. Presidental address. [Read before the Lancashire, Cheshire and N. Staffordshire Branch of the Association of Mining Electrical Engineers]. Being chiefly a commentary on the Home Office Regulations governing the use of electricity in mines. 4to. 19 pp. *n.p.*, 1918

ARNOLD, E., and LA COUR, J. L. Der Kaskadenumformer. Seine Theorie, Berechnung, Konstruktion und Arbeitsweise. 8vo. 80 pp. *Stuttgart*, 1904

BAILLEHACHE, R. E. J., *Comte* DE. Unités électriques. 8vo. 211 pp. *Paris*, 1909

BELLUZZO, G. Le turbine a vapore ed a gas. 8vo. 428 pp. *Milano*, 1905

BREMNER, D. A. Some features and requirements of the industrial situation. Address, Shipping, Machinery and Engineering Exhibition, Olympia, London. [The British Engineers' Association]. 8vo. 16 pp. *London*, 1919

BRITISH ENGINEERING STANDARDS ASSOCIATION. [Publications]. No. 7, 47, 81, 86, 89, 90, 103, 104. 8vo. *London*, 1919

7, British standard specification for dimensions of insulated annealed copper conductors for electric power and light, including pressure tests. [Revised July, 1919.]
47, British standard specification and sections for steel fishplates for British standard bull head railway rails (for rails from 70 lbs. to 100 lbs. per yard inclusive) and for British standard flat bottom railway rails (for rails from 25 lbs. to 100 lbs. per yard inclusive). [Revised June, 1919.]
81, British standard specification for instrument transformers.
86, British standard specification of magnetos for aircraft purposes. (Superseding no. 80, 1917).
89, British standard specification for indicating ammeters, voltmeters, wattmeters, frequency and power-factor meters.
90, British standard specification for recording (graphic) ammeters, voltmeters and wattmeters.
103, British standard specification for falling weight testing machines for rails.
104, British standard sections of light flat bottom railway rails and fishplates. (For rails from 10 to 20 lbs. per yard inclusive.)

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BRUNELLI, I. La costruzione delle linee elettriche aeree per telegrafi, telefoni, trasporti industriali e trazione elettrica. 8vo. 326 pp. *Roma*, 1912

CANADA. DEPT. OF THE INTERIOR. DOMINION WATER POWER BRANCH. Annual report for the year[s] ending March 31, 1914–17. [*The Report ending* 31 *March*, 1914, *has title* Report of the Superintendent of Water Powers]. 4 vol. 8vo. *Ottawa*, 1915–18

—— Water resourses paper[s]. No. 1-4, 7, 8, 10–14, 16–22, 27. 8vo. *Ottawa*, 1914–1919

1, Carson, P. A. Report on Railway Belt Hydrographic Survey for 1911-12.
2, Hendry, M. C. Report on Bow river power and storage investigations. Seasons 1911–13. [Maps, 1 vol.]
3, Johnston, J. T. Report on the Winnipeg river power and storage investigations. 2 vol.

4, 10, 22, Hendry, M. C. Progress report of the Manitoba Hydrographic Survey for 1912–16. 3 vol.
7, McLean, D. L., Scovil, S. S., and Johnston, J. T. Report on the Manitoba water-powers.
8, 14, 18, 21, Swan, R. G. Report of the British Columbia Hydrographic Survey for 1913–16. 4 vol.
10, Johnston, J. T. General guide for the compilation of water power reports, and the securing of field data.
11, Dunn, T. H. Report on Pasquia reclamation project.
12, Beale, A. M. Report on small water powers.
13, Conway, G. R. G. Report on the Coquitlam-Buntzen hydro-electric development, British Columbia.
16, Water powers of Canada. Being a reprint of a series of five monographs.
17, Mitchell, C. H. Canadian hydraulic power development and electric power in Canadian industry.
20, Kensit, H. E. M. Report on the interests dependent on Winnipeg river power, with special reference to the capital invested and the labour employed.
27, Johnston, J. T. Central electric stations in Canada. part II, Directory (Jan. 1, 1919).
For pt. 1 of this report (Statistics) *see* Canada, Dominion Bureau of Statistics, Census of Industry, 1917; 1919.

CANADA. DOMINION BUREAU OF STATISTICS. CENSUS OF INDUSTRY, 1917. Central electric stations in Canada. part 1, Statistics. 8vo. *Ottawa*, 1919
For pt. 2 of this report (Directory, by J. T. Johnston), *see* Canada, Dept. of the Interior; Water Power Branch: Water resources paper, no. 27, 1919

CAPART, G. La protection des réseaux et des installations électriques contre les surtensions. 8vo. 201 pp. *Paris*, 1914

COURSEY, P. R. Telephony without wires. 8vo. 433 pp. *London*, 1919

CROTCH, A. Telegraphy. An elementary text-book on the principles of electricity as applied to telegraph systems. 8vo. 165 pp. *London*, 1919

CURIE, P. Œuvres. Publiées par les soins de la Société Française de Physique. 8vo. 643 pp. *Paris*, 1908

DELLA SALDA, C. Macchine dinamo-elettriche e trasformatori statici. 8vo. 268 pp. *Milano*, 1912

DEVAUX-CHARBONNEL, X. État actuel de la science électrique. Phénomènes, applications, théories. 8vo. 660 pp. *Paris*, 1908

EASON, A. B. Flow and measurement of air and gases. 8vo. 264 pp. *London*, 1919

EDLER, R. Berechnung und Konstruktion elektrischer Schaltapparate (Grundlagen für den Entwurf von Schaltanlagen). 8vo. 449 pp. *Hannover*, 1909

—— Entwurf von Schaltungen und Schaltapparaten (Schaltungstheorie). Band 1. 8vo. 202 pp. *Hannover*, 1905

FLEMING, J. A. The thermionic valve and its developments in radiotelegraphy and telephony. 8vo. 294 pp. *London*, 1919

GERARD, E., and BAST, O. DE. Exercices et projets d'électrotechnique. tome 1, Applications de la théorie de l'électricité et du magnétisme. 8vo. 245 pp. *Paris*, 1907

HÄFNER, P. Stromverteilungssysteme und Berechnung elektrischer Leitungen. 8vo. 332 pp. *Hannover*, 1906

HOLLARD, A., and BERTIAUX, L. Analyse des métaux par électrolyse. Métaux industriels, alliages, minerais, produits d'usines. 8vo. 180 pp. *Paris*, 1906

INDIA, HYDRO-ELECTRIC SURVEY OF. Preliminary report on the water power resources of India; ascertained during the season 1918–1919. Compiled by J. W. Meares. folio. 115 pp. *Calcutta*, 1919

KAPP, G. The principles of electrical engineering and their application. vol. 2. 8vo. 395 pp. *London*, 1919

LAMB, C. G. Notes on magnetism for the use of students of electrical engineering. 8vo. 102 pp. *Cambridge*, 1919

LANFRANCO, M. Le frodi nei misuratori elettrici. Diagnosi e rimedi. sm. 8vo. 288 pp. *Milano*, 1908

LIEBENTHAL, E. Praktische photometrie. 8vo. 460 pp. *Braunschweig*, 1907

MARRO, A. Impianti elettrici a correnti alternate semplici, bifasi e trifasi. 2a ed. sm. 8vo. 798 pp. *Milano*, 1907

MELBOURNE. The electrification of the metropolitan railway system of Melbourne, Victoria, Australia. Published by authority. fol. 64 pp. *Melbourne*, 1919

MONASCH, B. Elektrische Beleuchtung. 2e Aufl. 2 Teil. [Bound in 1 vol.] 8vo. *Hannover*, 1910

MONIER, E. La télégraphie sans fil, la télémécanique et la téléphonie sans fil a la portée de tout le monde. 7e éd. 8vo. 249 pp. *Paris*, 1913

MONTPELLIER, J. A. L'électricité à l'Exposition Universelle et Internationale de Liége (1905). 8vo. 524 pp. *Paris*, 1906

MORGAN, J. D. Principles of electric spark ignition in internal combustion engines. 8vo. 88 pp. *London*, 1920

NIETHAMMER, F. Berechnung und Konstruktion der Gleichstrommaschinen und Gleichstrommotoren. 8vo. 586 pp. *Stuttgart*, 1904

—— Elektrische Schaltanlagen und Apparate samt Grundlagen zur Projektierung elektrischer Anlagen. 8vo. 582 pp. *Stuttgart*, 1905

OGAWA, K. Telephonic transmission of superimposed circuits. [Japan, Dept. of Communications, Researches of the Electrotechnical Laboratory, no. 78]. 8vo. 53 pp. *Tokyo*, 1919

PELLAT, H. Cours d'électricité. tome 3, Electrolyse. —Electrocapillarité.—Ions et électrons. 8vo. 296 pp. *Paris*, 1908

POMEY, J. B. Cours d'électricité théorique professé a l'Ecole Professionnelle Supérieure des Postes et Télégraphes. tome 1. 8vo. 404 pp. *Paris*, 1914

RANKIN, R. Storage battery practice. A practical handbook on the manufacture and properties of electric accumulators and their installation and operation. 8vo. 176 pp. *London*, [1919]

RAPS, A. Elektrizität und Volkswohlfahrt. 8vo. 138 pp. *Berlin*, 1914

RODET, J. Actions physiologiques et dangers des courants électriques. 8vo. 87 pp. *Paris*, 1917

ROUTIN, J. L. Le réglage des groupes électrogènes. 8vo. 159 pp. *Paris*, 1908

SATTLER, G. Elektrische Traktion. 8vo. 166 pp. *Hannover*, 1905

SCHARLOTT, P. Die "Elektrische" Taschenbuch für das Betriebspersonal elektrischer Strassenbahnen sowie für den Schulgebrauch. sm. 8vo. 206 pp. *Leipzig*, [?1908]

SCHULZ, E. Wissenswertes aus dem Dynamobau für Installateure. sm. 8vo. 159 pp. *Hannover*, 1906

SHORE, A. Alternating current work. An outline for students of wireless telegraphy. sm. 8vo. 172 pp. *London*, 1919

THE INSTITUTION OF ELECTRICAL ENGINEERS.

No. 18. Feb. 1920. INSTITUTION NOTES. [ISSUED WITH No 288 OF THE JOURNAL.]

Arrangements for March 1920.

ORDINARY MEETINGS OF THE INSTITUTION.

(Thursdays.)

[To be held at the Institution of Civil Engineers, Great George-street, Westminster, S.W., at 6 p.m. (light refreshments 5.30 p.m.).]

Date.	*Author and Title of Paper.*
1920.	
11 Mar.	W. H. PATCHELL: "Notes on Operating a By-product Producer Gas Plant for Power and Heating." S. H. FOWLES: "Production of Power from Blast Furnace Gas."
18 Mar.	Adjourned discussion on the above papers by Messrs. W. H. PATCHELL and S. H. FOWLES.
25 Mar.	Discussion on: (*a*) "The Electrical Equipment of Artisan Dwellings" (With an Introductory Paper by Mr. L. MILNE); (*b*) The Report of the Earthing Sub-Committee of the Wiring Rules Committee.

WIRELESS SECTIONAL MEETING.

(Wednesday.)

[To be held at the Institution of Civil Engineers, Great George-street, Westminster, S.W., at 6 p.m. (light refreshments 5.30 p.m.).]

1920.	
17 Mar.	Captain P. P. ECKERSLEY: "Duplex Wireless Telephony: Some Experiments on its Application to Aircraft."

INFORMAL MEETINGS.

(Mondays.)

[To be held in the Lecture-hall of the Chartered Institute of Patent Agents, Staple Inn Buildings (South Block), W.C., at 7 p.m.].

1920.	
1 Mar.	R. E. DICKINSON: "The Future of Labour in the Engineering Industry."
15 Mar.	J. W. BEAUCHAMP and S. M. HILLS: "Industrial Electrial Heating."
29 Mar.	(To be announced later.)

MEETINGS OF TERRITORIAL CENTRES.

Date.	*Place of Meeting.*	*Author and Title of Paper.*
1920.		
1 Mar.	Bristol	Prof. D. ROBERTSON: "Electric Clocks" (Lecture).
8 Mar.	Middlesbrough	S. H. FOWLES: "Production of Power from Blast Furnace Gas."
8 Mar.	Newcastle	Major K. EDGCUMBE, R.E. (T.): "The Protection of Alternating-Current Distribution Systems without the Use of Special Conductors."
9 Mar.	Edinburgh	Major K. EDGCUMBE, R.E. (T.): "The Protection of Alternating-Current Distribution Systems without the Use of Special Conductors."
9 Mar.	Leeds	J. SHEPHERD: "Failures of Turbo-Generators and Suggestions for Improvements."
9 Mar.	Manchester	W. H. PATCHELL: "Notes on Operating a By-product Producer Gas Plant for Power and Heating." S. H. FOWLES: "Production of Power from Blast Furnace Gas."
15 Mar.	Liverpool	Lieut.-Col. H. E. O'BRIEN, D.S.O.: "The Application of the Electric Locomotive to Main-Line Traction on Railways."
17 Mar.	Birmingham	Major K. EDGCUMBE, R.E. (T.): "The Protection of Alternating-Current Distribution Systems without the Use of Special Conductors."
20 Mar.	Sheffield	D. KERR: "Electric Winders."
22 Mar.	Newcastle	S. H. FOWLES: "Production of Power from Blast Furnace Gas."
23 Mar.	Manchester	Major K. EDGCUMBE, R.E. (T.): "The Protection of Alternating-Current Distribution Systems without the Use of Special Conductors."
23 Mar.	Sheffield	J. L. THOMPSON: "Transformers for Electric Furnaces."
24 Mar.	Birmingham	(To be announced later.)

STUDENTS' SECTION.

MEETINGS.

Date.	*Author and Title of Paper.*
1920.	
5 Mar.	Address by the President, Mr. ROGER T. SMITH. [*At the City and Guilds (Engineering) College, South Kensington, 7 p.m.*]
19 Mar.	J. SCOTT-TAGGART, M.C.: "The Vacuum Tube as a Transmitter and Receiver of Continuous Waves." (*At the City and Guilds Technical College, Leonard-street, Finsbury, E.C., 7 p.m.*)

VISITS TO WORKS.

Date.	*Time.*	*Works to be Visited.*
1920.		
12 Mar.	2 p.m.	Messrs. Peck Frean and Co.'s Works, S.E.
26 Mar.	2 p.m.	Lot's-road Generating Station.

The above visits, for which tickets of admission are necessary, are open only to Students of the Institution, and those wishing to attend should notify Mr. H. T. Body, 54 Chadwick-road, Leytonstone, E. 11, at least 10 days before each visit. In some cases the number forming the party is limited by the authorities of the works to be visited, and on these occasions

the Committee will decide by ballot or otherwise which Students may attend.

STUDENTS' SMOKING CONCERT.

Date.	*Time.*	*Place of Meeting.*
1920.		
12 Mar.	7.30 p.m.	Imperial Hotel, Russell Square, W.C.

Summer Meeting, 1920.

It is proposed to hold a Summer Meeting of the Institution from Tuesday, 13th July, to Friday, 16th July, at the Western Centre. Cardiff will be the headquarters, and there will also be visits to Hereford and Swansea. Further particulars will be announced shortly.

New Local Honorary Secretaries.

Mr. H. B. Poynder has been appointed Honorary Secretary of the North-Eastern Centre in place of Mr. L. H. A. Carr, and Mr. A. J. Ostler has succeeded Mr. A. J. Newman as one of the Joint Honorary Secretaries of the Western Centre.

Sub-Centres.

The following is a list of Sub-Centres of the Institution already formed :—

Parent Centre.	*Sub-Centre.*	*Name and Address of Hon. Secretary.*
North-Eastern	Tees-side	R. M. LONGMAN, Hinton's Buildings, Middlesbrough.
North Midland	Sheffield	J. D. BAILIE, 65–67 Prudential Buildings, Park-row, Leeds.
North-Western	Liverpool	O. C. WAYGOOD, 50 Manor-road, Meols, Hoylake.
.. ..	Preston	J. F. SIMPSON, Corporation Tramways, Deepdale, Preston.
Scottish	Aberdeen	A. GARDNER, Electricity Works, Milburn-street, Aberdeen.
South Midland	East Midland	J. F. DRIVER, Technical College, Loughborough.

Local Centre in Argentina.

The Council have approved the formation of a Local Centre of the Institution in Argentina, and the following Local Committee has been appointed:—

ARGENTINA LOCAL CENTRE COMMITTEE.

J. T. Cornish.
A. C. Kelly.
W. C. Laidler.
V. Lindop.
H. L. Randolph.
L. B. Trant.
J. Wilson.

Journal.

The Council have decided to publish in the form of a supplement to last year's volume (vol. 57) of the *Journal* the papers and discussions held over from previous Sessions, the publication of which had been deferred on account of the paper shortage.

Examinations.

The Council have decided to cancel the suspension of the Examination for Associate Membership, which will be imposed on all candidates not having passed one of the exempting examinations or submitted a satisfactory thesis, whose applications are received after the 29th February, 1920. In the case of applicants who have attained the age of 35 the Council may, in their discretion, dispense with the examination or thesis.

Informal Meetings.

The eighth Informal Meeting was held on Monday, 2nd February, 1920, at 7 p.m., at the Chartered Institute of Patent Agents, Staple Inn Buildings, W.C., Dr R. D. Gifford in the chair.

Major T. Rich, O.B.E., gave a discourse entitled "Engineering Experiences during the War," and in the subsequent discussion the following took part :—Major A. E. Levin, Major R. Grierson, Messrs. J. Coxon, G. C. Allingham, M.B.E., A. C. Brown, H. Laws Webb, W. F. Andrews, B. Lakeman, M. D. Hart, F. W. Bissett, and — Whitgift.

The ninth Informal Meeting was held on Monday, 16th February, 1920, at 7 p.m., at the Chartered Institute of Patent Agents, Staple Inn Buildings, W.C., Mr. S. M. Hills in the chair.

Mr. A. B. Eason opened a discussion on "Automatic Telephony for Private Branch Exchanges," in which the following took part :—Dr. R. D. Gifford, Messrs. A. F. Harmer, M. D. Hart, F. Shipton, R. Scruby, A. H. Allen, W. J. Oswald, T. W. Smith, F. Morley Ward, M. R. Gardner, F. Pooley, G. J. D. Scott, and J. R. Bedford.

Overseas Trade.

The Institution has received the subjoined letter (see page 11) from the Department of Overseas Trade, and in this connection a Member of the Council has prepared the

following prefatory note, which it is hoped will prove helpful in making known the Department's arrangements for facilitating the work of British traders abroad:—

As is already widely known, the Commercial Intelligence Service of the Government has recently undergone considerable development. The Consular Service is being re-organized, and special prominence is being given to commercial matters in the work of all Consular Officers.

Salaried Consular Officers, as distinct from Trading (i.e. unsalaried) Consular Officers, are appointed to all centres of commercial importance throughout the world. So many misconceptions are prevalent with regard to the unsalaried service that a few remarks are advisable in this connection. For many years past only British subjects have been allowed to be members of the salaried service, and the numerous questions as to the presence of aliens in the ranks of the Consular Service are due to the fact that the distinction between the salaried and unsalaried services is not commonly known. Where commercial or other considerations justify the appointment of a whole-time representative, a salaried Consul is appointed belonging to the regular service. Candidates for the regular service must not only be British-born subjects, but their origin and connections are also carefully scrutinized. Unsalaried Consular Officers are appointed at posts where circumstances do not warrant the expense of maintaining a salaried post, but where, on the other hand, the presence of some British representative is of distinct advantage to British travellers, merchants, or shipping. Valuable services have in many cases been rendered by such officers in the past. Wherever possible, British subjects are appointed to these unsalaried posts, and in point of fact the great majority of unsalaried Consular Officers are British subjects. Where a British subject is not available, but where it is nevertheless desirable that a British Consular post should be established, the honorary services of citizens of a friendly country are accepted, always provided that their standing, connections, and dispositions are found to be satisfactory. It should be added that such unsalaried officers work under the supervision and control of the regular Consul-General or Consul within whose district their duties are performed.

In addition to the Consular Service, the Commercial Diplomatic Service has been rapidly developed during the past two years. About 50 commercial counsellors and secretaries have now been appointed to embassies and legations throughout the world.

Whereas the duties of the Consul are local and detailed, those of the Commercial Diplomatic Officer are central and general. Tariff changes, import and export regulations or restrictions, legislation or legal decisions affecting companies, patents, concession rights, or industry, fall within the sphere of the Commercial Diplomatic Officers. So also does the cultivation of friendly relations with the officials of the central Government of the country, who are particularly connected with finance and commerce. The Commercial Diplomatic Officer studies the commercial and industrial problems of the country as a whole, whereas the attention of the Consul is focused upon his own particular consular district. For commercial intelligence purposes the Consular Officer is under the supervision and control of the Commercial Diplomatic Officer, and is, in fact, in his own district the eyes and ears of the Commercial Diplomatic Officer at the capital.

As an indication of the prominence which is being given to the commercial work of our representatives abroad it may be noted that the Department of Overseas Trade in London is now the headquarters of both the Commercial Diplomatic and the Consular Services.

It is realized that if the Department and its Officers abroad are to carry out their functions efficiently, close touch must be maintained with British manufacturers and exporters. The following letter, which has been issued to all technical institutions and trade associations in the country, is welcome evidence of the desire for the co-operation with traders which now pervades the official Commercial Intelligence Organization.

[COPY.]

DEPARTMENT OF OVERSEAS TRADE
(Development and Intelligence),
4, Queen Anne's Gate Buildings, S.W. 1.
1st November, 1916.

D.O.T. 101139 S.C.

SIR,

I am directed to inform you that cases have recently occurred in which delegations of British industries and trades have visited foreign countries and various parts of the Empire without His Majesty's Diplomatic or Consular Officers or His Majesty's Trade Commissioners having been advised beforehand of the visit, or notified of their arrival.

The result has been that His Majesty's Consular Officers and Trade Commissioners have lost an opportunity of rendering assistance, and of discussing matters connected with British trade of very great interest to them.

I am, therefore, to suggest that you should furnish early notice of any such visits in which you may be interested in order that this Department may notify His Majesty's Consular Officers and other Officers abroad concerned.

It will be useful to have particulars of the numbers of the delegation, the object of the visit, the organization on whose behalf it is made, and, if possible, the name of the hotel or hotels at which they will stay, and any other relevant information.

Might I also ask you to recommend British firms when sending representatives abroad on a business tour to instruct their representatives to call on His Majesty's Consular Officers in the countries they visit and on the Commercial Diplomatic Officer in the capital of each country, and, in the case of the Dominions, on His Majesty's Senior Trade Commissioner.

The object of this Department is to bring the commercial, diplomatic, consular and kindred services into closer personal touch with British firms, and I feel sure that we can rely on your co-operation in the matter.

Yours faithfully,
(Signed) L. A. PAISH,
for Comptroller-General.

Benevolent Fund.

Donations from the following were reported by the President at the Ordinary Meeting held on the 22nd January last (see *Journal*, 1920, vol. 58, p. 200) :

W. J. Addison, F. S. Adkins, H. Alabaster, C. T. Allan, P. F. Allan, P. R. Allen, A. Anderson, H. M. Anderson, O. M. Andrews, T. C. Angus, "Anonymous," R. Ardis, A. Arnold, K. N. Arnold, C. J. Aston, L. B. Atkinson, T. Austin, T. H Baines, F. J. Baldwin, P. E. Bamford, P. J. Barnes, B. Barber, A. H. Bate, M. Beales, J. S. Bean, F. G. Beaton, A. J. Beckett, J. T. Becklade, E G. Bell, E. E. Benham, H. W. Bennett, F. P. Best, N. Binks, J. Birch, W. Bird, D. H. Bishop, J. W. Black, H. E. Blackiston, E. H. Bond, C. A. Boraston, A. McD. Bower, E. Braathen, W. D. Brakenridge, S. E. Britton, S. K. Broadfoot, H. Brooke, J. S. Brown, W. Brown, Brig.-Gen. W. Baker Brown, G. H. Browne, G. L. Bruce, H. L. Buckman, J. Burbridge, R. B. Burrowes, W. Burton, P. H. C. Butcher, W. M. H. Butcher, A. S. Butler, J. H. Buttress, L. C. Bygrave, E. E. Calvert, F. C. Campbell, S. Carlisle, W. B. H. Carr, A. F. Carter, A. Castello-Sosa, J. E. Catt, W. A. Chamen, G. S. Chapman, H. C. Charlton, C. B. Chartres, F. G. Clark, R. L. Cleaver, J. Colquhoun, N. J. Cook, W. C. Cooke, A. Cooper, G. P. Cooper, F. Cope, G. L. Coventon, A. W. Cox, H. E. Cox, L. C. Cox, S. Craig, F. W. Crawter, B. Croft, L. H. Crowther, W. R. D. Crowther, A. Cunnington, J. F. Dale, I. S. Dalgleish, J. D. Dallas, I. C. J. Dalton, D. P. Davies, G. H. Davies, B. Davis, B. Dennis, B. Drew, G. L. Drury, W. H. Duncan, H. Dutton, P. C. Ebner, Dr. W. H. Eccles, H. S. Edwin, L. H. Euler, B. A. Evans, G. H. D. Evans, T. K. Evans, S. Evershed, C. D. Farmer, L. G. Fenner, A. H. Finlay, A. P. M. Fleming, O.B.E., G. H. Fletcher, W. Fletcher, H. S. Fox, F. H. Francis, A. J. French, F. G. Frost, R. A. Frost, J. G. Garnes, Dr. C. C. Garrard, Sir John Gavey, C.B., H. P. Gaze, F. W. Geoghegan, J. Gibbins, H. W. Gilbert, H. Gill, V. W. Gill, M. McA. Gillespie, C. G. Glass, H. Gobie, A. E. Gott, E. H. Gould, L. C. Grant, H. J. Grapes, O. V. Greaves, W. B. Green, F. A. Greene, R. E. Grime, C. Grover, E. A. Guthrie, H. J. Hadrill, R. C. Hall, C. E. Hambleton, M. D. Hart, T. Martin Harvey, L. F. Haslam, F. B. O. Hawes, W. J. Head, Q. McG. Henderson, J. F. Herd, F. W. M. Herring, C. J. Hickleton, R. J. B. Hippisley, H. Hirst, W. E. Hobbs, J. P. Hodges, A. J. Hodgson, W. T. Hodgson, W. Hodson, P. M. Hogg, H. J. Holden, T. Hollins, S. Holmes, T. Holmes, T. Hood, W. F. M. Horne, J. A. B. Horsley, A. J. Howard, E G. Humfress, R. W. Humm, O. Inman, Admiral of the Fleet Sir H. B. Jackson, G.C.B., H. H. Jacques, C. James, S. James, B. M. Jenkin, L. Jessop, J. H. Johnson, P. S. Jolin, C. Jones, C. H. Jones, F. H. Jones, I. Jones, M. Karuven, R. Keen, W. A. Ker, P. C. Kerr, F. G. Ketélbey, D. Kingsbury, J. E. Kingsbury, W. Kingsland, J. R. Kingston, E. O. Kirkby, H. Kitchen, M. Klein, G. H. Langdon, J. L. Langton, W. J. Larke, O.B.E., F. A. Lawson, W. Y. Lee, A. Lees, J. W. Lewsley, E. W. Lewis, P. H. Lissenden, W. A. R. Long, R. P. Lovell, A. C. Lowe, J. R. P. Lunn, J. M. Macaulay, A. McClelland, C. N. McDermott, C. F. C. Macfarlane, J. C. Macfarlane, Prof. J. T. MacGregor-Morris, D. W. McIntyre, R. S. McLeod, H. McNaul, W. L. McPherson, R. F. J. Maidment, Sir H. Mance, C.I.E., E. Manville, P. M. Martin, T. H. Matthews, J. M. S. Maxwell, A E. May, J. Meredith, C. H. Merz, P. Miley, H. W. Miller, J. Mirrey, J. Mitchell, L. E. Mold, E. J. Moore, W. M. N. Morecombe, R. Morley, E. R. Morris, W. M. Morrison, S. R. Mullard, M.B.E., H. E. Munday, H. A. Nevill, C. G. M. New, A. D. Newbury, A. J. Newman, F. A. Nicholls, J. K. A Nicholson, H. Nimmo, H. A. Nott, A. G. Nye, T. Oliphant, F. L. Otter, E. A. Paris, G. R. J. Parkinson, E. Parry, H. Parry, H. Paterson, J. V. Peacock, S. L. Pearce, C.B.E., A. C. Pegg, G. K. Perkins, F. H. Pernet, W. F. T. Pinkney, F. C. Porte, E. E. R. Porter, L. Purves, G. S. Ram, A. J. Ramsay, H. A. Ratcliff, W. R. Rawlings, R. H. Redman, J. P. Rees, S. K. Reeves, P. E. Restrepo, F. Richardson, R. Rigg, E. S. Ritter, D. E. Roberts, George Robinson, Granville Robinson, J. H. Robinson, W. M. Robinson, H. Rocky, A. I. Rogers, G. D. Rogers, G. Ross, L. L. Ruderman, Dr. A. Russell, B. G. C. Russell, J. W. Hyde, F. Samuelson, H. Savage, H. M. Sayers, J. E. Sayers, R. H. Schofield, E. Seddon, W. M. Selvey, E. E. Sharp, H. Shaw, J. Shaw, W. Shaw, W. Shead, W. H. Shephard, J. E. Shepherd, W. E. E. Sich, N. S. Sim, A. F. Skinner, J. W. Slorach, J. H. Smart, B. Smith, C. G. Smith, E. L. Smith, G. Smith, Prof. S. P. Smith, D.Sc., C. H. Smyth, M. Solomon, A. Sommerville, J. H. Southern, T. Stanley-Thomas, A. L. Stanton, H. B. Stanton, T. F. Stent, F. Stinson, C. Stirling, H. Stokes, C. D. Stoneham, R. W. Stubbington, A. L. Tackley, W. J. Targett, J. Taylor, J. E. Taylor, F. J. Teago, A. W. Thomas, J. Thomas, T. Rees-Thomas, F. A. Thompson, N. A. Thompson, K. J. Thomson, M.B.E., H. Tinsley, J. Toulmin, A. Travers, H. W. Tremayne, E. J. Turnbull, D. J. Unwin, C. J. Vaughan, B. J. Vine, O. V. Waddington, H. Walker, C. S. Wallbridge, T. C. T. Walrond, W. G. Walter, E. J. Ward, S. H. C. Webster, W. Weir, E. J. Wells, D. Welsford, H. D. Wilkinson, J. W. Wilkinson, J. W. Williams, A. D. Williamson, E. Williamson, Prof. E. Wilson, J. P. Winn, K. L. Wood, C. H. Wordingham, C.B.E., H. G. Wright, J. E. Wright, Colonel Commanding, Officers and Men of Royal Engineers Volunteers (per Sir J. Snell).

THE INSTITUTION OF ELECTRICAL ENGINEERS.

No. 19. Mar. 1920. INSTITUTION NOTES. [ISSUED WITH No. 289 OF THE JOURNAL.]

Arrangements for April and May, 1920.

ORDINARY MEETINGS OF THE INSTITUTION.

(*Thursdays.*)

[To be held at the Institution of Civil Engineers, Great George-street, Westminster, S.W., at 6 p.m. (light refreshments 5.30 p.m.).]

Date.	*Author and Title of Paper.*
1920	
15 Apr.	C. V. Drysdale, O.B.E., D.Sc.: "Modern Marine Problems" (Eleventh Kelvin Lecture).
29 Apr.	A. E. McColl: "Automatic Protective Devices for Alternating-current Systems."
13 May	S. Evershed: "Permanent Magnets, in Theory and Practice."
20 May	Annual General Meeting.

INFORMAL MEETING.

(*Monday.*)

[To be held in the Lecture-hall of the Chartered Institute of Patent Agents, Staple Inn Buildings (South Block), W.C., at 7 p.m.]

1920	
19 Apr.	G. H. Ayres: "Group versus Individual Driving."

MEETINGS OF TERRITORIAL CENTRES AND SUB-CENTRES.

Date.	*Place of Meeting.*	*Author and Title of Paper.*
1920		
12 Apr.	Cardiff	Prof. F. Bacon: "Thermionic Valves."
13 Apr.	Manchester	Annual General Meeting and Smoking Concert.
13 Apr.	Glasgow	J. M. M. Munro: "Highland Water Power."
14 Apr.	Birmingham	Discussion on "Faults and Troubles in Electric Apparatus and Installations."
19 Apr.	Liverpool	Annual General Meeting of Liverpool Sub-Centre. C. V. Drysdale, O.B.E., D.Sc.: "Modern Marine Problems" (Eleventh Kelvin Lecture).
19 Apr.	Newcastle	Annual General Meeting. Major T. Rich, O.B.E.: "Electricity in the Western War Zone."
20 Apr.	Leeds	Major K. Edgcumbe, R.E. (T.): "The Protection of Alternating-current Distribution Systems without the use of Special Conductors."
20 Apr.	Manchester	C. V. Drysdale, O.B.E., D.Sc.: "Modern Marine Problems" (Eleventh Kelvin Lecture).
21 Apr.	Birmingham	C. V. Drysdale, O.B.E., D.Sc.: "Modern Marine Problems" (Eleventh Kelvin Lecture).
23 Apr.	Newcastle	C. V. Drysdale, O.B.E., D.Sc.: "Modern Marine Problems" (Eleventh Kelvin Lecture).
30 Apr.	Dundee	L. Milne: "The Electrical Equipment of Artisan Dwellings."
3 May	Swansea	(To be announced later.)
11 May	Leeds	Annual General Meeting. Discussion on: (*a*) "The Electrical Equipment of Artisan Dwellings" (with an Introductory Paper by Mr. L. Milne); (*b*) The Report of the Earthing Sub-Committee of the Wiring Rules Committee.

STUDENTS' SECTION.

Meetings.

Date.	*Author and Title of Paper.*
1920	
12 Apr.	Joint Discussion with the Graduates Association of the Institution of Mechanical Engineers on "The Six-hour Working Day, and its effect on Industry." (*At the Institution of Mechanical Engineers, Storey's Gate, St. James's Park, S.W., 8 p.m.*)
16 Apr.	J. Scott-Taggart, M.C.: "The Vacuum Tube as a Transmitter and Receiver of Continuous Waves." (*At Faraday House, Southampton Row, W.C., 7 p.m.*).
30 Apr.	J. E. Holmstrom: "Tidal Power." (*At the City and Guilds Technical College, Leonard-street, Finsbury, E.C., 7 p.m.*)
14 May	E. G. Humfress: "Electrical Motor Control Devices." Annual General Meeting. (*Place of Meeting to be announced later.*)

Visits to Works.

Date.	*Time.*	*Works to be Visited.*
1920		
23 Apr.	2 p.m.	Imperial Paper Mills, Gravesend.
— May	2 p.m.	L.B. & S.C.R. Locomotive Works, Brighton and Lancing.

The above visits, for which tickets of admission are necessary, are open to Students of the Institution, and those wishing to attend should notify Mr. H. T. Body, 54 Chadwick-road, Leytonstone, E. 11, at least 10 days before each visit. In some cases the number forming the party is limited by the authorities of the works to be visited, and on these occasions the Committee will decide by ballot or otherwise which Students may attend.

Council Nominations for Election to the Council.

The following have been nominated by the Council for the vacancies which will occur in the offices of President, Vice-Presidents, Honorary Treasurer, and Ordinary Members of Council on the 30th September, 1920 :—

President. (*One Vacancy.*)

Ll. B. Atkinson.

Vice-Presidents. (*Three Vacancies.*)

Dr. W. H. Eccles. J. S. Highfield.
S. L. Pearce, C.B.E.

Honorary Treasurer. (*One Vacancy.*)

Sir J. Devonshire, K.B.E.

Ordinary Members of Council.

Members. (*Six Vacancies.*)

F. Gill, O.B.E. A. P. Pyne.
P. V. Hunter, C.B.E. Dr. A. Russell.
J. F. Nielson. F. Ryan.
W. Noble. W. O. Smith.

Students' Premiums and Prizes.

In place of one Premium of £10 and several of £5 hitherto awarded each Session for papers read before the Students' Sections, the Council have decided to award in future three Premiums of the value of £15 each.

The Council have also accepted an offer from the British Electrical and Allied Manufacturers' Association of prizes of £10 each (up to a total value of £100 for the first year) for the best papers by Students of the Institution on electrical subjects, suitable for publication in the B.E.A.M.A. *Journal*. The method of award is as follows :—

(*a*) *For papers read at Students' Meetings.*

At the end of the Session the Papers Committee will recommend for publication in the B.E.A.M.A. *Journal* the most meritorious among the Students' papers which have not been awarded premiums by the Institution.

(*b*) *For papers not read at Students' Meetings but offered direct for publication in the B.E.A.M.A. Journal.*

These papers must be sent to the Honorary Secretaries of the Students' Sections for transmission to the Secretary of the Institution, who will submit them to the Papers Committee. This Committee will recommend whether they should be published or not in the B.E.A.M.A. *Journal*. The fact of a paper being published in the B.E.A.M.A. *Journal* will not preclude it from being read and discussed at a Students' Meeting.

Informal Meetings.

The tenth Informal Meeting was held on Monday, 1st March, 1920, at 7 p.m., at the Chartered Institute of Patent Agents, Staple Inn Buildings, W.C., Mr. G. C. Law in the chair.

Mr. R. E. Dickinson opened a discussion on "The Future of Labour in the Engineering Industry" in which the following took part: Dr. R. D. Gifford, Messrs. R. Rankin, J. W. Beck, W. J. Oswald, W. E. Warrilow, S. M. Hills, A. B. Eason, M. D. Hart, A. G. Hilling, W. J. Ricketts, A. Murdoch, and G. C. Law.

The eleventh Informal Meeting was held on Monday, 15th March, 1920, at 7 p.m., at the Chartered Institute of Patent Agents, Staple Inn Buildings, W.C., Mr. W. L. Wreford in the chair.

A discussion on "Industrial Electric Heating," with an introductory paper by Messrs. J. W. Beauchamp and S. M. Hills, was opened by the latter. The following took part in the discussion: Dr. R. D. Gifford, Major R. Grierson, Messrs. E. P. Barfield, G. H. Ayres, W. J. Oswald, R. E. Dickinson, W. E. Rogers, J. C. Rennie, F. W. Adcock, V. O. Haddock, W. E. Warrilow, H. P. Gaze, F. Harmer, A. G. Whyte, H. Craske and F. Pooley. Mr. J. W. Beauchamp replied to the points raised by the speakers.

Benevolent Fund.

Donations from the following were reported by the President at the Ordinary Meeting held on the 11th March last:

A. G. Akehurst, J. W. Alexander, G. A. Allan, G. Allom, C. Allsop, R. Anderson, L. Andrews, A. N. Arman, J. W. Arthur, C. C. Atchison, H. S. E. Austin, J. F. Avila, H. J. Aylott, C. J. Baker, G. H. Baker, C. M. Ballard, A. S. Barnes, S. Beeton, C. H. Bennett, J. F. M. Bennett, H. Birch, E. J. Black, R. S. C. Blance, R. F. P. Blennerhassett, C. W. Boxall, H. R. Broadbent, W. Briggs, R. P. Brousson, C. F. Browne, A. E. Brookes, W. H. Brownjohn, R. H. Bryans, F. La T. Budgett, H. S. Bulley, W. E. Burnand, J. Burns, A. C. Campbell, F. W. Capper, J. H. Carrick, A. F. Carter, H. J. Cash, W. Casson, H. C. Channon, D. S. Charles, R. A. Chattock, A. R. Chaytor, E. V. Cheney, B. G. Churcher, City of Glasgow Royal Engineers Volunteers (per Major E. T. Goslin), R. C. L. Clark, J. C. Clarke, B. C. Clayton, W. C. Clinton, H. W. Clothier, G. D. Coe, R. T. Coe, F. G. Cole, A. Collins, J. B. Colquhoun, A. D. Constable. R. Cook, W. K. Cook, J. R. Cowie, A. W. Cox, Hon. E. H. Cozens-Hardy, Captain E. W. Creak, C.B., F.R.S., C.

Crompton, F. R. Davenport, J. F. Davie, B. Davies, F. E. Davies, J. Davies, A. Davy, D. S. Dearden, Sir A. Denny, Bart., Sir J. Devonshire, K.B.E., E.W. Dickinson, T. J. Digby, H. Diggle, W. E. Doran, H. M. Dowsett, B. M. Drake, J. D. Drury, C. V. Drysdale, D.Sc., Major K. Edgcumbe, H. J. Eley, C. J. A. Ellis, F. E. Elmore, F. T. C. Emberton, C. W. Emanuel, A. G. Everett, E. Fawsett, S. E. Fedden, A. B. Field, C. E. Field, J. H. Field, A. J. Fippard, R. G. Fleming, W. S. Flight, Prof. C. L. Fortescue, M. W. Foulkes-Roberts, G. R. H. Frith, E. C. Fry, A. Fuchs, E. Garcke, W. H. Gatley, J. Gell, D. C. Gerrard, H. E. Gibbard, H. J. Gibson, F. Gill, Sir R. T. Glazebrook, K.C.B., F.R.S., G. F. C. Gordon, W. F. Gordon-Campbell, J. R. W. Grainge, H. W. Gregory, F. Y. Grepe, W. G. Griffith, L. Griffiths, W. H. F. Griffiths, F. E. Gripper, C. W. Gwyther, D. K. Hall, W. Hall, E. Halton, A. S. Hampton, P. H. Harding, G. H. Hardwick, R. Hardy, L. S. Harley, N. E. P. Harris, P. Harris, A. J. Harrison, H. T. Harrison, A. W. Harrold, F. de B. Hart, F. N. Haward, J. R. Hawes, C. C. Hawkins, C. E. Hawkins, W. C. C. Hawtayne, K. Hedges, D. Henriques, F. W. Highfield, J. S. Highfield, L. B. Hobgen, C. C. Hodges, W. A. Hole, R. Holland-Pryor, A. S. Hollin, H. C. Holroyd, A. Howard, F. Howard, J. Hunter-Gray, C. G. Huntley, E. S. Jacob, E. W. James, W. L. James, F. K. Jewson, Dr. G. Kapp, A. C. Kelly, J. C. Kelso, Sir A. B. W. Kennedy, F.R.S., W. T. Kerr, W. E. Kidner, C. S. Kieran, H. Kingsbury, P. P. Kipping, V. R. Krohn, J. W. Laing, W. E. Lane, T. Langlois, K. E. Latimer, M. Le Clezio, A. H. Leeves, E. Lerpinière, A. E. Levin, H. J. Lewis, H. R. Lloyd, J. Longbottom, O. D. Lucas, W. T. MacCall, G. M. Macilwraith, D. A. McLean, A. W. R. Macpherson, Prof. E. W. Marchant, W. J. Marston, J. Martin, T. D. Martin, T. N. Martin, V. Martin, S. W. Melsom, W. G. Messer, Midland Electrical Engineers' Ball Committee (per G. J. Bish), L. B. Miller, T. H. Minshall, A. P. Mitchell, A. T. K. Moir, H. T. Moody, W. M. Mordey, W. C. Mountain, G. Murray, E. J. Nichols, J. F. Nielson, H. W. Nimmo, A. M. Niven, C. G. Nobbs, A. C. Norman, R. J. O'Brien-Owen, Sir A. M. J. Ogilvie, K.B.E., C.B., C. Oliver, V. F. M. Oliver, Lt.-Col. W. A. J. O'Meara, C.M.G., A. Page, F. T. Parker, E. J. Parnall, A. D. C. Parsons, W. H. Patchell, W. Pate, Com. Q. H. Paterson, D.S.C., R.N., E. R. Patrick, B. Paul, F. G. Payne, D.S.O., J. V. Payne, J. D. Peattie, W. O. Pepper, H. L. Percy, L. W. Phillips, J. W. Piggott, D. F. Pilkington, H. V. Pointon, A. H. Preece, N. Prentice, H. F. Proctor, J. R. Protheroe, A. P. Pyne, R. H. Rawll, J. H. Reyner, T. Rich, H. J. W. Ridley, H. R. Rivers-Moore, P. R. Rice, C. G. Richards, R. Robertson, B. A. Robinson, P. Rocks, W. R. Rogers, S R. Roget, T. Roles, P. Rosling, G. L. Rosser, A. H. Rowles, S. A. Russell, H. E. Sancto, H. R. Sanders, R. H. Saul, H. S. Saunders, J. Sayers, F. H. Schroeder, W. H. Scott, S. Sharp, H. C. Shepherd, G. H. Shortridge, A. Siemens, F. A. Simpson, H. A. Skelton, Sir W. Slingo, A. R. Smith, J. A. Smith, Sir J. Snell, J. B. Snell, N. V. Snipe, B. Snowball, C. E. Springsguth, F. H. Starling, W. H. Steele, J. H. Stephens, A. C. Stewart, C. Stewart, W. C. Stewart, F. P. O. Strange, Rev. R. H. Streatfeild, Prof. H. Stroud, D.Sc., W. S. Stuart, A. J. Stubbs, H. S. Styan, H. W. Sullivan, J. H. Targett, E. E. Tasker, G. Taylor, J. R. Thavenot, L. Thomas, F. Thompson, B. Thomsett, J. S. Thomson, C. H. R. Thorn, R. G. Torry, M. H. Tovey, R. D. Trevor-Roper, A. P. Trotter, E. Turner, J. W. Turner, G. K. Tweedy, D. J. Unwin, J. H. Valentine, H. C. Vereker, C. Vernier, Lt.-Col. W. A. Vignoles, D.S.O., E. Walker, H B Walker, J. Walker, Prof. Miles Walker, D.Sc., F. Wardrobe, C. E. Warner, A. Warwick, C. T. Waterhouse, F. Waters, E. C. Watson, R. W. Weekes, C. G Westerhout, J. W. Wheeler, H. Whewell, E. A. Wilbraham, H. Williams, N. J. Wilson, W. Wilson, A. N. G. Wood, W. J. H. Wood, W. B. Woodhouse, J. H. Woodward, J. H. Woolliscroft, W. A. Wordley, E. L. Wright, W. R. Wynne, H. E. Yerbury, and H. W. Young.

Accessions to the Lending Library.

BEST, W. N. The science of burning liquid fuel.
8vo. 159 pp. *London*, 1913

COURSEY, P. R. Telephony without wires.
8vo. 433 pp. *London*, 1919

DICK, J. R., and FERNIE, F. Electric mains and distributing systems.
2nd ed. 8vo. 476 pp. *London*, 1919

FLEMING, J. A., *D.Sc.*, *F.R.S.* The principles of electric wave telegraphy and telephony.
4th ed. 8vo. 722 pp. *London*, 1919

—— The propagation of electric currents in telephone and telegraph conductors.
3rd ed. 8vo. 384 pp. *London*, 1919

—— The thermionic valve and its developments in radiotelegraphy and telephony.
8vo. 294 pp. *London*, 1919

GERHARDI, C. H. W. Electricity meters. Their construction and management.
2nd ed. 8vo. 524 pp. *London*, 1917

HILL, J. G. Telephonic transmission: theoretical and applied. 8vo. 414 pp. *London*, 1920

KAPP, G. The principles of electrical engineering and their application. 2 vol. (1, Principles. 2, Application.) 8vo. *London*, 1916–19

KENNEDY, W. S. General conditions in electrical and other engineering contracts. With an introduction by Sir A. B. W. Kennedy.
1a. 8vo. 120 pp. *London*, 1920

RANKIN, R. Storage battery practice. A practical handbook on the manufacture and properties of electric accumulators and their installation and operation. 8vo. 176 pp. *London*, [1919]

SHORE, A. Alternating current work. An outline for students of wireless telegraphy.
sm. 8vo. 172 pp. *London*, 1919

STANLEY, R. Text-book on wireless telegraphy. New ed. 2 vol. 8vo. *London*, 1919
1, General theory and practice.
2, Valves and valve apparatus.

STILL, A. Electric power transmission. Principles and calculations. Including a revision of "Overhead electric power transmission."
2nd ed. 8vo. 425 pp. *New York*, 1919

—— Principles of transformer design.
8vo. 228 pp. *New York*, 1919

WALKER, S. F. Electric mining machinery.
8vo. 387 pp. *London*, [1919]

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AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS, THE. Standardization rules. Approved by the Board of Directors. Nov. 8, 1918.
8vo. 133 pp. *New York*, 1918

BLAKE, E. Selected studies in elementary physics: a handbook for the wireless student and amateur.
8vo. 184 pp. *London*, 1920

BLIZARD, J., and MALLOCH, E. S. Results of forty-one steaming tests conducted at the Fuel Testing Station, Ottawa. [Canada: Dept. of Mines: Mines Branch, Bulletin no. 27].
8vo. 83 pp. *Ottawa*, 1920

BLYTHE, E. A text book on machine drawing for electrical engineers. Forming an introductory treatise on the construction of electrical machinery and apparatus. obl. fol. 88 pp. *Cambridge*, 1920

BRITISH ELECTRICAL AND ALLIED MANUFACTURERS' ASSOCIATION (INCORP.). Education and training for the electrical and allied engineering industries. Being a Report of the Education Committee of the B.E.A.M.A. sm. 8vo. 64 pp. *London*, 1920

DOWSETT, H. M. Wireless telegraphy and telephony: first principles, present practice and testing.
8vo. 362 pp. *London*, 1920

ELECTRICITY (SUPPLY) ACT, 1919. [9 & 10 Geo. 5, Ch. 100.] 1a. 8vo. 34 pp. [*London*, 1920]

FLEMING, J. A., *D.Sc., F.R.S.* The propagation of electric currents in telephone and telegraph conductors. 3rd ed. 8vo. 384 pp. *London*, 1919

HILL, J. G. Telephonic transmission: theoretical and applied. 8vo. 414 pp. *London*, 1920

HYDRO-ELECTRIC POWER COMMISSION OF ONTARIO. Rules and specifications for test and approval of electrical material, devices and fittings for use or sale in the Province of Ontario.
8vo. *several pagin., n.p.* [1919]

MARTIN, M. J. Wireless transmission of photographs. 2nd ed. 8vo. 158 pp. *London*, 1919

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8vo. 280 pp. *London*, 1919

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8vo. 387 pp. *London*, [1919]

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—— Synchronmaschinen für Wechsel- und Drehstrom. ihre Wirkungsweise, Berechnung und Konstruktion. 8vo. 156 pp. *Hannover*, 1905

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1, Der einphasige Wechselstrom.
2, Mehrphasige Wechselstrome und Wechselstromsysteme.
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4, Wechselstromtransformatoren und Wechselstrommotoren.

THE INSTITUTION OF ELECTRICAL ENGINEERS.

No. 20. April 1920. INSTITUTION NOTES. [ISSUED WITH No. 290 OF THE JOURNAL]

Arrangements for May and June, 1920.

ORDINARY MEETINGS OF THE INSTITUTION.

[At 6 p.m. (light refreshments 5.30 p.m.)]
Annual General Meeting 5.30 p.m. (light refreshments 5 p.m.)

Date.	*Author and Title of Paper.*
1920.	
Thursdays, at the Institution of Civil Engineers, Great George-street, Westminster.	
13 May	S. Evershed: "Permanent Magnets, in Theory and Practice."
20 May	Annual General Meeting (**at 5.30 p.m.**).
Wednesdays, at the Institution of Mechanical Engineers, Storey's Gate, Westminster.	
16 June	Discussion on the following: Paper read before the Royal Society of Arts by Sir Dugald Clerk, K.B.E., D.Sc., F.R.S., entitled "Distribution of Heat, Light and Motive Power by Gas and Electricity." "The Report on the Coal-Gas and Electrical Supply Industries of the United Kingdom to the President of the Institution of Gas Engineers," by Sir Dugald Clerk, K.B.E., D.Sc., F.R.S., Professor Arthur Smithells, C.M.G., F.R.S., and Professor J. W. Cobb, C.B.E., B.Sc.
30 June	P. Dawson: "Overhead and Live-rail Conductor Systems."

WIRELESS SECTIONAL MEETING.

1920.	
Wednesday, at the Institution of Mechanical Engineers, Storey's Gate, Westminster, S.W., at 6 p.m. (light refreshments 5.30 p.m.).	
9 June	M. Latour: "High-frequency Machines."

MEETINGS OF TERRITORIAL CENTRES.

Date.	*Place of Meeting.*	*Author and Title of Paper.*
1920.		
3 May	Swansea	C. V. Drysdale, O.B.E., D.Sc.: "Modern Marine Problems" (Eleventh Kelvin Lecture).
11 May	Leeds	Annual General Meeting. L. Milne: "The Electrical Equipment of Artisan Dwellings."
9–12 June	Kinloch-leven	Summer Outing of Scottish Centre.

STUDENTS' SECTION.

Date.	*Author and Title of Paper.*
1920.	
14 May	Annual General Meeting. E. G. Humfress: "Electrical Motor Control Devices." (*At King's College, Strand. W.C.*)

Annual General Meeting, 20 May, 1920.

The Annual General Meeting of the Institution (Members, Associate Members, and Associates only) will be held at the Institution of Civil Engineers, Great George-street, Westminster, S.W., on Thursday, 20th May, 1920, at 5.30 p.m., to receive and consider the Annual Report of the Council and the Accounts for the year ended 31st December, 1919, and to elect Auditors.

The Report and Accounts will be found on pages 308–324 of the present Number of the *Journal* (No. 290).

Nominations for Election to the Council.

In addition to those members nominated by the Council (see *Institution Notes*, No. 19, page 14) the following have been nominated for the vacancies which will occur in the Council on the 30th September next:—

As Ordinary Members of Council.

R. F. Ferguson: (*Nominated* by Messrs. H. Bell, O.B.E., C. A. Blascheck, J. K. Brydges, J. Christie, T. Hesketh, E. W. Lancaster, A. H. Shaw, C. B. Smith, C. H. Smyth, W. B. Thorpe and R. N. Torpy.)

A. H. W. Marshall: (*Nominated* by Messrs. J. A. Anderson, E. Cox-Walker, J. H. Holmes, J. Leggat, J. R. P. Lunn, W. McLellan, J. Pigg, S. G. Redman, O.B.E., R. P. Sloan, C.B.E., J. W. Spark, P. S. Thompson, C. Vernier and J. Wright.)

C. Vernier: (*Nominated* by Messrs. F. G. C. Baldwin, J. R. Blaikie, E. W. Dickinson, R. D. Fairclough, E. Fawssett, F. T. Hall, T. L. Horn, H. C. Lamb, A. H. W. Marshall, C. D. Taite, A. M. Taylor, W. M. Thornton, O.B.E., D.Sc., C. Turnbull, P. P. Wheelwright and J. C. Wigham.)

Mr. Addenbrooke's Lectures on Dielectrics.

Mr. Addenbrooke's lectures on "Dielectrics in Electric Fields," which were given before the Institution last year (20th February, 6th and 13th March), will be published in book form by Messrs. Constable & Co. in the early autumn.

An epitome of the lectures will be found in the Institution *Journal* (*Institution Notes*, No. 10, January 1919, page 13).

Wireless Section.

The following Rules were approved by the Council at a meeting held on the 15th April, 1920 :

WIRELESS SECTION.

1. For the purpose of ascertaining which members of the Institution shall be deemed to be members of the Wireless Section, a circular shall be sent to each member of the Institution in the United Kingdom, and to each member in the United Kingdom who may be elected in the future, inquiring whether—

> "he is actively engaged in the study, design, manufacture, or operation of Wireless or High-Frequency Engineering Apparatus."

Members replying in the affirmative and otherwise entitled to the privileges of membership of the Institution shall be deemed to be members of the Section.

WIRELESS COMMITTEE.

2. The Committee shall be constituted as follows :—

The Chairman of the Wireless Section.
The President I.E.E. (ex-officio).
The Chairman of the Papers Committee (ex-officio).
One member of Council elected by the Council.

12 Ordinary Members who shall be members of the Institution elected by ballot of the members of the Wireless Section.

Not more than four representatives nominated annually by Government Departments at the invitation of the Council, but such nominees shall not have a vote in connection with Clauses 5, 6 and 8.

3. The Chairman of the Section (who shall also be Chairman of the Committee) shall be a Member (M.I.E.E.) of the Institution. He shall retire annually and shall not hold office more than two years in succession.

4. No Ordinary Member of the Committee shall serve on the Committee more than three years in succession.

5. One-third of the Ordinary Members of the Committee shall retire annually. For the first two years the Ordinary Members of the Committee shall determine which of the original Ordinary Members shall retire.

ELECTION OF COMMITTEE.

6. (*a*) Not later than the 31st May in each year the Committee shall publish a list of names of duly qualified persons whom they nominate for the vacancies about to occur in the Committee on the 30th day of September next following.

(*b*) Not later than 14 days after the publication of the Committee's list of nominations, any five members of the Wireless Section may nominate any other duly qualified person to fill any vacancy by delivering such nomination in writing to the Secretary, together with the written consent of such person to accept office if elected, but each such nominator shall be debarred from nominating any other person for the same election.

(*c*) Thereupon, if any other candidate or candidates have been duly nominated, the Committee shall send to each member of the Wireless Section entitled to vote a ballot paper containing the names of all persons duly nominated, stating which persons are nominated by the Committee and giving the names of not more than five of the members by whom every other person (if any) is nominated.

(*d*) Every member voting shall erase sufficient names to reduce the number of names on the ballot paper after such erasure to the number to be elected to the respective offices.

(*e*) The ballot papers shall be returned so as to reach the Secretary not later than the eighth day after the day of issue, and the votes recorded shall be counted by two or more scrutineers appointed by the members at a Wireless Sectional Meeting. The result of the ballot shall be reported by the scrutineers to the President of the Institution.

(*f*) But if no other candidate or condidates have been nominated under the provisions of Clause (*b*) above, those nominated by the Committee shall be considered duly elected.

(*g*) The persons elected under this Clause shall take office on the 1st day of October next following. The Committee's year of office shall begin on the 1st day of October of each year and end on the 30th September next following.

7. The office of a member of the Committee shall *ipso facto* be vacated : (*a*) If he become bankrupt or lunatic ; or (*b*) If by notice in writing to the Institution he resign his office, or (*c*) If he (not being a member of the Committee nominated by a Government Department) cease to be a member of any class of the Institution.

8. Vacancies on the Committee other than those arising under Clauses 3, 4, and 5 above shall be filled by the Committee, but the period of office of a person so elected shall end on the same date as that on which the vacating member would normally have retired, and at the end of such period he shall not be eligible for immediate re-election as a member of the Committee.

9. Any cases of doubt or difficulty as to election to or retirement from the Committee shall be decided by the Committee.

POWERS OF THE COMMITTEE.

10. The Committee shall organize Sectional Meetings for the reading and discussion of papers on Wireless Telegraphy, Wireless Telephony, High-Frequency Engineering and cognate subjects.

11. The Committee shall have power to appoint Sub-Committees to consider and report to the Committee upon any matter of interest to Wireless and High-Frequency Engineers, but shall not have power to take action or to communicate with persons or bodies outside the Institution without the sanction of the Council.

International Electrotechnical Commission.

The Secretary of the Institution has received the following for publication :—

Meetings of the Advisory Committees of the International Electrotechnical Commission were held in Brussels from March 27th to 31st inclusive. In addition to the secretaries, about 35 delegates were present from eight different countries.

The delegates were welcomed on behalf of the Belgian Electrotechnical Committee by M. Omer de Bast, of the Institute Montefiore, and on the opening day they were entertained at lunch by the members of the Belgian Committee. The Conferences were held at the Offices of the State Railway Administration.

Rating.—The first Volume of the I.E.C. Rating Rules for Electrical Machinery for machines not exceeding 5,000 volts, 750 k.v.a. rated output and 50 cm. in length axially, having been previously approved for issue, the Meeting therefore devoted most of its time to consideration of questions which would apply to larger machines.

In regard to high-voltage tests, it was agreed to recommend to the National Committees that the dielectric tests given for the smaller machines in Volume 1 of the I.E.C. Rules should apply also to large machines, with the exception of turbo-alternators. In regard to the latter, the French Committee's proposals that the high-voltage tests on turbo-alternators and similar machines should be increased, have been referred to the National Committees for consideration.

The use of embedded temperature detectors for the acceptance tests of electrical machinery was again discussed and, whilst it was generally agreed that these should be used in the case of large machines, there is still a very considerable difference of opinion as to the limit above which the use of this method of measurement should be compulsory, and the question will need further consideration.

The American Committee recommend the use of embedded temperature detectors for all rotating machines larger than those dealt with in Volume 1 of the I.E.C. Rules, whereas the British Committee propose their compulsory use for acceptance tests only for :—

(1) Turbo-generators and similar machines over 5,000 k.v.a. whatever the voltage and core length.
(2) Other rotating machines over 90 cm. core length, whatever the k.v.a. and voltage, or over 65 cm. core length, if over 6,000 volts whatever the k.v.a.

In regard to the terminal markings given in Appendix 1 of the I.E.C. Rules, it has not been agreed to recommend these for adoption, as the American Committee have pointed out that it is undesirable to fix terminal markings for transformers until terminal markings for motor and control apparatus have been settled. The American Committee has been invited to forward a specific recommendation on this point.

Graphical symbols.—The British delegates submitted the British list of graphical symbols prepared, but not yet issued. This list had been based on the proposals received from the Italian National Committee, the B.E.A.M.A., and many other sources, and it is gratifying to record that many of them have been adopted for recommendation to the National Committees for acceptance internationally.

Nomenclature.—The work on nomenclature which has been suspended during the war was commenced. The general principles upon which the work should be developed were discussed, and it was decided :—

(*a*) To prepare an international electrotechnical vocabulary taking into consideration all the existing national vocabularies. Each National Committee to add a translation of the definitions in its own language in a national edition. The vocabulary shall be compiled so as to include a definition of the word in English and French and in such a way that there will be no difficulty in finding, either in the vocabulary or in an appendix, the equivalent words in the various other languages.

(*b*) That the different National Committees communicate to the Central Office as soon as possible the work which they have already done in this direction.

With regard to the question of adding translations of other languages, it was felt that it would not be possible in the official publications to extend beyond the official languages of the I.E.C., namely, English and French.

In order to hasten the work, a Sub-Committee was appointed consisting of one delegate from each of the following countries :—Great Britain, United States of America, Belgium, France, Holland, Spain, Italy and Switzerland ; and a meeting of this Sub-Committee is to be held at Zurich some time in June, Professor Wyssling having kindly undertaken to make the necessary arrangements and to do all he can to assist.

The following recommendation proposed by M. Paul Janet was accepted for reference to the National Committees :—

In view of the fact that—

(*a*) It is of the greatest importance to unify the electrotechnical nomenclature and symbols in every country,
(*b*) It is equally of the greatest importance that new electrotechnical terms, definitions and symbols should be formulated from the point of view of international usage,
(*c*) There is a more or less widespread tendency towards the adoption, in various cases, of electrotechnical terms, definitions and symbols which too often do not anticipate nor lend themselves to international use.

The Advisory Committees on Nomenclature and Symbols feel that it is very desirable that the National Committees should exercise in their respective countries a moral influence to prevent or to stop the formulation of electrotechnical terms, definitions and symbols which would ultimately present a serious obstacle to international agreement.

Standard pressures.—The Advisory Committee on Standard Pressures for Insulators considered various proposals which had been submitted by the National Committees, and finally formulated a series of standard high pressures together with the proposals for the high-

pressure test in each case. These proposals will be submitted to the various National Committees for their consideration.

It is proposed to hold the next meeting of these Committees in Paris in November.

A Report of each of the meetings, giving the proposals in detail, will be available very shortly.

Accessions to the Reference Library.

BUCK, A. M. Some graphical solutions of electric railway problems. [University of Illinois, Engineering Experiment Station, Bulletin no. 90].
8vo. 36 pp. *Urbana, Ill.*, 1916

DUNN, H. H. The tractive resistance of a 28-ton electric car. [University of Illinois, Engineering Experiment Station, Bulletin no. 74].
8vo. 53 pp. *Urbana, Ill.*, 1914

HADFIELD, *Sir* R., *Bart.* Introductory address to be read at the Symposium on the Microscope: its design, construction and application, in which the following Societies take part: The Faraday Society, The Royal Microscopical Society, The Optical Society, The Photomicrographic Society. Jan. 14th, 1920. 8vo. 42 pp. [*London*], 1920

—— The great work of Sorby, to be read at the Symposium on the Microscope, Jan. 14th, 1920.
8vo. 5 pp. [*London*], 1920

—— Photomicrographs of steel and iron sections at high magnification, to be read at the Symposium on the Microscope, Jan. 14th, 1920.
8vo. 6 pp. pl. A–H. [*London*], 1920

—— The work of the Faraday Society, and a brief reference to Michael Faraday, to be read at the Symposium on the Microscope, Jan. 14th, 1920.
8vo. 7 pp. [*London*], 1920

HYDRO-ELECTRIC POWER COMMISSION OF ONTARIO. Electric generating and transmission systems.
Map. folded 8vo. [1920 ?]

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2nd ed. sm. 8vo. 469 pp. *London*, 1920

KENNELLY, A. E. The speed of electricity. [A reprint from The Wireless Age, Aug., 1919].
8vo. 7 pp. *n.p.*, 1919

—— and VELANDER, E. Alternating-current plane-vector potentiometer measurements at telephonic frequencies. [Massachusetts Institute of Technology, Electrical Engineering Dept., Research Div., Bulletin no. 20. Reprinted from Proc. Amer. Phil. Soc., vol. 58, 1919].
8vo. 36 pp. *n.p.*, 1919

—— —— A rectangular-component two-dimensional alternating-current potentiometer. [Massachusetts Institute of Technology, Electrical Engineering Dept., Research Div., Bulletin no. 18. Reprinted from the Journal of the Franklin Institute, July, 1919].
8vo 26 pp. *n.p.*, 1919

KERSHAW, J. B. C. The use of low-grade and waste fuels for power generation.
8vo. 212 pp. *London*, 1920

LYON, W. V. Current distribution in armature conductors. [Massachusetts Institute of Technology, Electrical Engineering Dept., Research Div., Bulletin no. 19. Reprinted from Electrical World, July 12, 1919].
sm. 8vo. 12 pp. *n.p.* [1919]

MOULTON, H. F., and EVANS-JACKSON, J. H. The Patents, Designs, and Trade Marks Acts. With notes on all recent decisions and changes in law and practice.
la. 8vo. 144 pp. *London*, 1920

NEALE, R. E. Electricity: its production and applications.
sm. 8vo. 144 pp. *London, n.d.*

PARLIAMENTARY PAPERS. MINISTRY OF MUNITIONS OF WAR: MUNITIONS INVENTIONS DEPT. Nitrogen Products Committee. Final report.
fol. 363 pp. *London*, 1919

RAYMOND-BARKER, E. Cable-fault localisation graphs in practice. [Reprint of articles published in the "Electrical Review," 1909].
8vo. 68 pp. [*London*, 1909]

—— Graphs in a cable-ship drum-room: notes for junior assistants. [Reprints of articles published in the "Electrical Review," Jan. 17th, 1913, et seq.].
la 8vo. 46 pp. *London* [1913]

—— Hand-book in cable-break localisation. Graphic methods. The calculator board in practice. [Reprint of articles published in the "Electrical Review," 1903–1904].
8vo. 66 pp. [*London*, 1904]

—— The two-tone vibrating transmitter and cable inductive signalling. [Reprint of articles published in "The Electrician," Dec. 18th, 1908, and Jan. 15th, 1909].
8vo. 27 pp. *London*, [1909]

RYMER-JONES, J. Localising high-resistance breaks in cables. [Reprinted from the "Electrical Review," July 24th–Aug. 14th, 1908].
4to. 11 pp. [*London*, 1908]

—— Universal methods for computing the speed of a telegraphic message sent by automatic transmitter or hand-key.
fol. 19 pp. [*London*, 1911]

SCHMIDT, E. C., and DUNN, H. H. The tractive resistance on curves of a 28-ton electric car. [University of Illinois, Engineering Experiment Station, Bulletin no. 92].
8vo. 54 pp. *Urbana, Ill.*, 1916

SCHWEIZERISCHE ELEKTROTECHNISCHE VEREIN, DER. Vorschriften betreffend Erstellung und Instandhaltung elektrischer Hausinstallationen, herausgegeben vorn Schweiz. Elektrotechnischen verein.
4te Aufl. sm. 8vo. 169 pp. [*Zürich*], 1919

SOUTH AFRICAN RAILWAYS. Report on the introduction of electric traction. [By] Merz and McLellan.
fol. 48 pp., 9 tables and 6 pl. *London*, 1919

THOMPSON, J. S., and THOMPSON, H. G. Silvanus Phillips Thompson, D.Sc., LL.D., F.R.S. His life and letters.
8vo. 383 pp. *London*, [1920]

WHITE, A. V. and VICK, C. J. Water powers of British Columbia. Including a review of water power legislation relating thereto and a discussion of various matters respecting the utilization and conservation of inland waters. [Canada: Commission of Conservation].
la 8vo. 653 pp. *Ottawa*, 1919

WHITTAKER'S ELECTRICAL ENGINEER'S POCKET-BOOK. Edited by R. E. Neale. Founded by K. Edgcumbe. 4th ed.
sm. 8vo. 682 pp. *London*, 1920

THE INSTITUTION OF ELECTRICAL ENGINEERS.

No. 21. May, 1920. INSTITUTION NOTES. [ISSUED WITH No. 291 OF THE JOURNAL.]

Arrangements for June, 1920.

ORDINARY MEETINGS OF THE INSTITUTION.

(Wednesdays.)

[To be held at **The Institution of Mechanical Engineers**, Storey's Gate, Westminster, S.W., at 6 p.m. (light refreshments 5.30 p.m.).]

Date. 1920.	*Author and Title of Paper.*
16 June	Discussion on the following: Paper read before the Royal Society of Arts by Sir DUGALD CLERK, K.B.E., D.Sc., F.R.S., entitled "Distribution of Heat, Light and Motive Power by Gas and Electricity." "The Report on the Coal-Gas and Electrical Supply Industries of the United Kingdom to the President of the Institution of Gas Engineers," by Sir DUGALD CLERK, K.B.E., D.Sc., F.R.S., Professor ARTHUR SMITHELLS, C.M.G., F.R.S., and Professor J. W. COBB, C.B.E., B.Sc.
30 June	P. DAWSON: "Overhead and Live-rail Conductor Systems."

WIRELESS SECTIONAL MEETINGS.

(Wednesdays.)

[To be held at **The Institution of Mechanical Engineers**, Storey's Gate, Westminster, S.W., at 6 p.m. (light refreshments 5.30 p.m.).]

Date. 1920.	*Author and Title of Paper.*
9 June	M. LATOUR: "High-frequency Machines."
23 June	B. S. GOSSLING: "The Development of the Three-Electrode Valve during the War."

TERRITORIAL CENTRES.

Date. 1920.	*Place of Meeting.*	
9–12 June	Kinloch-leven	Summer Outing of Scottish Centre.

Annual Conversazione.

The Annual Conversazioné will be held at the Natural History Museum, Cromwell Road, South Kensington, by permission of the trustees of the Museum, on Thursday, 1st July, from 8 p.m. to 11 p.m.

Council for the Year 1920–21.

The result of the ballot for the vacancies which will occur on the 30th September next was reported at the Annual General Meeting on the 20th May to be:—

President: L. B. Atkinson.

Vice-Presidents: Dr. W. H. Eccles, J. S. Highfield, and S. L. Pearce, C.B.E.

Honorary Treasurer: Sir James Devonshire, K.B.E.

Ordinary Members of Council (Members): F. Gill, O.B.E., P. V. Hunter, C.B.E., A. H. W. Marshall, W. Noble, Dr. A. Russell, and C. Vernier.

The Council for the year 1920–21 will therefore be constituted as follows:—

President.

L. B. Atkinson.

The Past-Presidents.

Vice-Presidents.

W. A. Chamen.
Dr. W. H. Eccles.
J. S. Highfield.
S. L. Pearce, C.B.E.

Honorary Treasurer.

Sir James Devonshire, K.B.E.

Ordinary Members of Council.

P. R. Allen, O.B.E.
H. J. Cash.
H. W. Clothier.
J. R. Cowie.
D. N. Dunlop.
S. E. Fedden.
E. A. Gatehouse.
F. Gill, O.B.E.
P. V. Hunter, C.B.E.
Prof. E. W. Marchant, D.Sc.
A. H. W. Marshall.
W. Noble.
C. C. Paterson, O.B.E.
Dr. A. Russell.
J. Sayers, O.B.E.
P. D. Tuckett.
C. Vernier.
B. Welbourn,

and

The Chairman and Immediate Past-Chairman of each Territorial Centre.

Premiums.

At the Annual General Meeting on the 20th May the President announced that the following premiums for papers have been awarded by the Council :—

The Institution Premium (*value* £25).

M. B. Field, O.B.E. — "The Navigational Magnetic Compass considered as an Instrument of Precision."

The Ayrton Premium (*value* £10).

W. H. Patchell. — "Notes on operating a By-product Producer Gas Plant for Power and Heating."

The Fahie Premium (*value* £10).

E. A. Laidlaw and W. H. Grinsted. — "The Telephone Service of Large Cities, with special reference to London."

The John Hopkinson Premium (*value* £10).

J. L. Thompson, M.Sc. — "Transformers for Electric Furnaces."

The Kelvin Premium (*value* £10).

H. W. Taylor. — "Eddy Current Losses in Stator Windings."

The Paris Premium (*value* £10).

G. Stead. — "The Short Tungsten Filament as a Source of Light and Electrons."

The Webber Premium (*value* £10).

Major A. C. Fuller, R.E. — "The Fullerphone and Its Application to Military and Civil Telegraphy."

A Premium (*value* £5).

Captain J. M. Scott Maxwell. — "Scientific Management : a Solution of the Capital and Labour Problem."

A Premium (*value* £5).

Major K. Edgcumbe, R.E. (T.). — "The Protection of Alternating-Current Distribution Systems without the Use of Special Conductors."

Wireless Section Premiums.

The Duddell Premium (*value* £20).

Captain H. J. Round, M.C. — "Direction and Position Finding."

A Premium (*value* £10).

Prof. C. L. Fortescue. — "The Design of Multiple-stage Amplifiers using Three-Electrode Thermionic Valves."

A Premium (*value* £10).

Prof. G. W. O. Howe, D.Sc. — "The High-frequency Resistance of Wires and Coils."

A Premium (*value* £10).

Captain L. B. Turner. — "The Oscillatory Valve Relay : a Thermionic Trigger Device."

Students' Premiums.

A Premium (*value* £15).

E. T. Norris. — "The Protection of Alternating-current Circuits and Apparatus."

A Premium (*value* £15).

J. Scott-Taggart, M.C. — "The Use of Vacuum Tubes for Wireless Transmission and the Reception of Continuous Waves."

A Premium (*value* £15).

C. E. Webb. — "The Principles of Scientific Illumination."

Informal Meetings.

The twelfth Informal Meeting was held on Monday, 19th April, 1920, at 7 p.m., at the Chartered Institute of Patent Agents, Staple Inn Buildings, W.C., Mr. F. Pooley in the chair.

Mr. G. H. Ayres opened a discussion on "Group versus Individual Driving," in which the following took part :—Messrs. W. E. Rogers, A. F. Harmer, A. E. Gott, J. M. L. Slater, J. R. Bedford, R. Rankin, P. M. Baker, W. L. Wreford, A. G. Hilling, R. Grierson, M. R. Gardner, W. E. Bradshaw, and G. J. D. Scott.

The Informal Meetings Committee have the programme for next session under consideration, and members are invited to indicate to the Secretary of the Institution subjects on which they may be willing to open a discussion. The Committee desire to remind members that at these meetings, which are strictly informal, smoking is allowed and the remarks of the speakers are not recorded or published.

War Memorial Book.

All efforts to trace the relatives of the following members who lost their lives during the War having failed, the Secretary would be glad to receive the addresses of their relatives or any particulars of their careers and military service that may be known to members :—

Gunner E. L. N. Cope (Student), Royal Horse Artillery.

2nd Lieut. C. T. Eaddy (Student), North Staffordshire Regiment.

Sapper E. A. I. Elkins (Associate Member), Royal Engineers.
Captain D. S. Laurie (Associate Member), Royal Engineers.
Captain S. Pilkington (Associate), Leicestershire Regiment.
2nd Lieut. S. M. Rawson (Student), Royal Fusiliers.
Gunner O. B. Reynolds (Student), New Zealand Artillery.
2nd Lieut. W. Winkworth (Associate Member), Northumberland Fusiliers.

R.E. War Memorial Scholarships.

The Secretary of the Institution has been requested to give publicity to the following :—

Applications for the following Educational Scholarships may now be sent to the Secretary R.E. War Benefits Committee, R.E. Institute, Chatham. The Committee, in adjudicating upon these applications will give primary consideration to the necessity of the case.

" A " Scholarships of £40 per annum, for children of Officers and Other Ranks of Royal Engineers, including Regulars, Special Reserve, Territorial Force, and New Army, who before the war were in a position to send their children to Public Schools, etc. Tenable between the ages of 10 and 18 years, the grants to be reviewed after four years. Ten scholarships at present available.

" B " Scholarships of £15 per annum, for children of Warrant Officers, N.C.O.'s, and Men, to assist the children to go on to a Technical or Secondary School. Tenable between the ages of 13 and 16 years. Forty scholarships at present available.

" C " Kitchener Scholarships. At present limited to one of £40, and two of £15, under the same conditions as *" A "* and *" B "* respectively.

Applications to be considered in the first adjudication should be received by the 1st June, 1920. Forms of application can be obtained from the Secretary of the R.E. War Benefits Committee.

For the present, owing to the large number of casualties in the Great War, the issue of these Scholarships will be confined to children or dependents of Officers and Other Ranks, either killed in action, died of wounds, or disease contracted in the service, or permanently disabled therein.

Joint Meeting at Calcutta with American Institute of Electrical Engineers.

A limited number of copies are available of the Proceedings at the Joint Meeting of the Calcutta Local Centre of the Institution with the American Institute of Electrical Engineers, held at Calcutta from 31st December, 1918, to 3rd January, 1919. Copies can be obtained from the Secretary of the Institution, 1, Albemarle Street, W. 1 (price, 10s. 6d. each).

The Proceedings include Addresses by the two Chairmen (Mr. J. W. Meares and Mr. H. P. Gibbs) and the following papers :—

N. N. Iengar ..	" Electric Boilers " (with report of discussion).
A. Hay and F. N. Mowdawalla	" The Starting Conditions in Synchronous Machines " (with report of discussion).
R. H. Martin ..	" The Problem of the Electrification of Mountain Railways, with special reference to the Nilgiri Railway " (with report of discussion).

Benevolent Fund.

Donations from the following were reported by the President at the Ordinary Meeting held on the 29th April last.

D. Adams, H. Armstrong, J. W. Atkinson, C. R. Barry, W. S. Barter, J. R. Beard, A. O. Buckingham, A. F. Burgess, J. M. Calder, R. H. Campion, E. Carter, F. S. Carter, A. J. Chesterton, J. R. Clayton, G. Cooper, G. W. Cooper, P. Copp, H. Creagh, R. L. Cribbes, W. Cuffley, E. Cunningham, H. Y. Denham, E. D. Dent, L. Doyle, A. H. Dykes, F. J. Edgar, L. Edwards, H. H. Eiriksson, W. Ellams, G. J. Evans, S. H. Fowles, W. A. Fraser, B. French, C. A. Friendship, D. M. Gault, F. J. Hancock, V. J. Hegney, H. J. Henwood, F. P. Holliday, R. V. Hook, H. J. Howard, V. R. Hurle, S. Insull, F. L. James, B. H. Jenkinson, C. J. Jewell, V. N. Jolliffe, W. H. M. Kelman, H. W. Kolle, W. H. Lea, L. J. Lepine, G. Lewis, F. W. Main, A. Martin, A. E. Mayes, F. C. Meaby, J. W. Meares, S. C. Miller, W. J. Minton, W. G. P. Mitchell, J. A. Morton, A. Munoz, P. de O. Novaes, L. E. H. Parker, L. Paysant, A. G. Phillips, E. A. K. Picard, A. Pickersgill, A. J. Price, S. Carrick Price, C. Rettie, J. Russell, C. W. Saddington, W. Samples, C. E. Sayer, E. W. Scott, J. H. Semple, A. Sevalho, F. Shakeshaft, I. Shirshov, G. M. S. Sichel, M. G. Simpson, L. Slattery, A. T. Smee, B. R. Smith, A. Strickland, W. H. T. Swire, W. C. P. Tapper, C. F. Thomas, D. C. Townley. H. J. Troughton, H. C. Wellden, A. T. Winder, and J. Wolfenden.

Roll of Honour.

(Fifteenth List.*)

Killed in Action.

Clarke, Private R. St. J.	New Zealand Trench Mortar Battery	Student

Died.

Bly, 2nd Lieut. H. A. E.	Royal Garrison Artillery	Student

* See *Journal I.E.E.*, vol. 54, pp. 64, 447 and 675; vol. 55, pp. 55, 193, 325, and 537; and *Institution Notes*, No. 1, p. 3; No. 4, p. 15; No. 7 p. 29; No. 9, p. 4; No. 11, p. 20; No. 12, p. 23, and No. 15, p. 40.

Military Honours Awarded.

(SIXTEENTH LIST.*)

C.M.G.

Harrison, Lieut.-Col. N., D.S.O.	South African Engineers	Associate Member

C.B.E.

Sankey, Captain H. R.	Royal Engineers	Member
Phillips, Bt.-Lieut.-Col. G. I.	General Staff	Associate

O.B.E.

Falle, Lieut.-Comm. H. de C.	R.N.V.R.	Associate Member
Kingston, Major J. R.	Royal Engineers	Associate Member

D.S.O.

McArthur, Captain R. T.	South African Engineers	Associate Member

M.B.E.

Webb, Lieut.-Col. G. R.	Indian Defence Force	Member
Huddart, Major A. H.	Royal Army Service Corps	Associate Member
Reeves, 2nd Lieut. J. H.	Royal Garrison Artillery	Associate
Robinson, Commander E. G., V.C.	Royal Navy	Associate Member
Platt, Captain C. B.	Royal Engineers	Student

M.C.

Gray, Captain R.	Royal Field Artillery	Associate Member
Hunt, Captain T. C.	Royal Engineers	Associate Member
Denton, Lieutenant R. H.	Royal Engineers	Student

Mentioned in Despatches.

Carty, Lieut.-Col. S. W., O.B.E., M.C.	Royal Army Service Corps	Associate Member
Crowther, Lieutenant J. P.	Royal Army Ordnance Corps	Associate Member
Derry, Lieutenant C.	Royal Army Service Corps	Student
Friend, Major R. H.	Royal Engineers	Associate Member
Fruhe-Sutcliffe, Major R.	Royal Engineers	Associate Member
Fulcher, Lieutenant E. W. P., M.B.E.	Norfolk Regiment	Associate Member
Hunt, Captain T. C.	Royal Engineers	Associate Member
Lockhart-Jervis, Major B. C., D.S.O.	Royal Engineers	Associate Member
McNaughton, Brig.-Gen. A. G. L., C.M.G., D.S.O.	Canadian Artillery	Associate Member
Riley, Lieutenant T. S., M.C.	Royal Army Service Corps	Student
Whitney, Corporal J. S.	Royal Engineers	Graduate

Mentioned.

Brown, Lieutenant Sir A. Whitten, K.B.E.	Royal Air Force	Member
Reeves, Flying Officer W. A.	Royal Air Force	Student
Vereker, Flight-Lieut. H. C.	Royal Air Force	Student
Voss, Lieutenant H. A.	Royal Engineers	Graduate

Legion d'Honneur, Officier.

Ditmas, Lieut.-Col. F. I. L., D.S.O., M.C.	Durham Light Infantry	Associate

Legion d'Honneur, Chevalier.

Cottrell, Commander W. H., C.M.G., O.B.E.	R.N.V.R.	Associate

Ordre de Leopold, Officier.

Ogilvie, Colonel Sir A. M. J., K.B.E., C.B., V.D.	Royal Engineers	Associate

Ordre de l'Etoile Noire.

Rich, Major T., O.B.E., T.D.	Royal Engineers	Associate Member

* See *Journal I.E.E.*, vol. 54, pp. 306, 518, and 674; vol. 55, pp. 56, 193, 325, and 537; and *Institution Notes*, No. 1, p. 3; No. 4, p. 15; No. 6, p. 24; No. 7, p. 30; No. 9, p. 4; No. 12, p. 23; No. 14, p. 30; No. 15, p. 40.

Roger J. Smith

PRESIDENT 1919-1920

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INAUGURAL ADDRESS

By ROGER T. SMITH, President.

(Address delivered 13 November, 1919.)

PRELIMINARY.

I sincerely thank you for the honour you have done me in electing me as your President. Coming as it does at a time when both railways and electricity supply are subject to fresh legislation, your choice of a railway electrical engineer ought to be appropriate; but it is obvious that this legislation adds greatly to the responsibilities of the Chair during this session. I can but do my best to justify your choice.

Although the hospitality of the Institution of Civil Engineers, continued for many years both before and during the war, has made us feel completely at home in this theatre, it is a great disappointment that our expectations during the summer of starting this session in our building have not been fulfilled. There is a possibility that evacuation will take place before the end of the session, but much will have to be done to render our Victoria-embankment house habitable before we can again work and meet there.

The signing and ratification of Peace with Germany is so great an event in history, that it must form the starting point of any address not dealing wholly with the past or with abstract ideas.

Yet I want to begin with two pre-war matters relating to the Institution, my railway and myself. In February last the Institution lost one of its three remaining original members,* Professor Carey Foster, who assisted at the birth of the Society of Telegraph Engineers in 1871 and sat on the first Council of the Society when it started its meetings on 28th February, 1872. He was President in 1881, when an Electrical Exhibition was held in Paris. This was undoubtedly the first clearing house for ideas and the stimulus to design for electrical engineers in Western Europe, and the part taken by the Institution in that memorable event is perhaps worth recalling.

The British Government having decided against appointing special commissioners to the Exhibition only six months before it opened, the Society of Telegraph Engineers, at the request of the French Government, secured the co-operation of English electrical engineers and manufacturers and satisfactory British exhibits were obtained in less than one month. When four months later it was clear that the British Section was going to be a success, the British Government, on the joint application of the Society of Telegraph Engineers and the Society of Arts, consented to appoint members from both Societies to represent this country as official commissioners, but at their own expense. This evidence of public spirit on the part of members of these two Societies is an example for all time to this Institution, while the incident is historical as one of the early instances of government action with regard to the electrical industry.

I had the good fortune to be taken to Paris to see the Electrical Exhibition. That experience, and the Exhibition of the following year at the Crystal Palace, fired me to become an electrical engineer, and my first electrical associations were with the spirited encouragement of the industry by this Institution in 1881 and with its then President the late Professor Carey Foster, who became in turn teacher, father-in-law, and friend.

The second historical matter I wish to refer to is the early connection of railways in general, and of my railway, the Great Western, in particular, with telegraphy and with the Society of Telegraph Engineers. Cooke and Wheatstone's four- and five-needle telegraph was patented in June 1837, tried in July of the same year between Euston and Camden Town, and installed on the Great Western Railway between Paddington and

* The other two original members still with us are Sir Herbert Jekyll K.C.M.G., and Colonel E. D. Malcolm, R.E.

West Drayton in 1838, the same year that saw the opening of the first section of the railway itself between Paddington and Maidenhead. This telegraph was extended to Slough four years later.

Practical telegraphy, that is to say, electrical engineering, started in this country on the railways for railway purposes, and although for public messages the telegraphs had been taken over by the Government before the Society of Telegraph Engineers was formed in 1871, the Society, and its successor the Institution, may with some truth be said to be the child of railway telegraphs. The telegraphs installed on the railways were used among other things for railway messages and for the announcement of the despatch of trains. Mr. Cooke saw that in conjunction with fixed signals the telegraphs could be used to provide an absolute block system on the railways by dividing the line into sections and, by telegraphing between signal boxes, to secure that one train only was permitted to be in a section at any one time. On the Great Western the Box Tunnel was worked on Cooke's block telegraph system in 1850.

The Electric Telegraph Company had already been installing and maintaining telegraphs for all purposes on the railways for some years, and Mr. C. E. Spagnoletti had been working for them on the Great Western Railway, when in 1853 that railway created the post of Telegraph Superintendent and appointed Mr. Spagnoletti to fill it. Mr. Spagnoletti, the first of the railway telegraph superintendents, filled the Great Western post for 37 years, and was the first railway President of this Institution, under its second title of the Society of Telegraph Engineers and Electricians, in 1885.

Railways have unfortunately taken so little part in the more recent activities of our Institution, that I have ventured to recall to both the historical connection of the railways with the first commercial applications of electricity in this country. The birth of the telegraphs led to the birth of this Institution, and the name of Mr. Spagnoletti, my predecessor at Paddington, will always be associated with the early developments of electric telegraphy.

Our Roll of Honour.

Public tributes during this year have been paid to those members of the Institution who have served through the war and to those who have fallen in that service. In addition, I only wish to remind you of our corporate and individual pride in those who have served and those who have fallen. Pride being a simple and not a complex emotion, like sympathy, we may all venture to show it even to strangers. I therefore wish the members of the Institution not to allow either their corporate or their individual pride in our victors or in our dead to diminish with time. No better evidence of that pride can be given than in fulfilling that "dear obligation" of the Royal Proclamation of September 15th last by the preferential employment of the disabled in electrical work for which they can be fitted. It is pleasant to think how important a part this Institution took in 1916 in starting the training of disabled men for switchboard and substation work.

The Problems of Peace.

The signing and ratification of Peace, and the problems which Peace has brought, are testing and will test the temper of the nation to the uttermost. I propose to consider how some of those problems may affect the electrical industry.

An outstanding feature of our public life, and of our Press, during the last few months has been and still is the passion for destructive criticism. However much some criticism may be justified, in affairs the man who criticizes without attempting to show the better way, or at least another way which he thinks to be better, is unfitting both himself and others for doing their duty.

For nearly five years the nations have been destroying each other and each other's property at enormous cost. It would almost seem as if the habit of destruction had so grown upon us, that now that the time has come for rebuilding society, every effort to do so is withered by fault-finding without any attempt to put forward a considered alternative. The Institution, from the nature of the profession which it represents, has among its members a large body of educated men who have been taught how to think, at least in their own subject. But that is not enough. The war has taught us that no man has the right to be only a specialist, and some of the present unrest is due to the refusal of the wage-earner to be a specialist for so large a part of each day that he cannot be anything else. Good citizenship is as important as a man's trade or profession, and just now good citizenship is essential both for our present and for our future. To bodies of educated men such as constitute this Institution, the nation must look for providing the constructive criticism essential to the formation of that public opinion which alone can enable a democratic government to succeed in creating society afresh. The phrase "constructive criticism" I think explains itself. It certainly does not embrace any of those panaceas which in the terms of the quack advertisements are to cure each and every disease of our civilization.

Education and Scientific Research.

It is the custom of Britons to decry their education and to compare it unfavourably with that of some other nations, but only the few spend time and thought and money to remedy agreed defects.

Although a parallel exists to some extent in the United States, this country is the original home of the expensive education at public school and university which may cost anything from £1,500 to £3,000. If considered only as a financial investment, it may appear a poor one, since boys with one-tenth of the expenditure on their education can obtain as good or better positions in the professions, in commerce, or in industry. But those who have enjoyed the privilege of the expensive British education with its many activities, among which learning and scholarship alone seem to be optional, realize what an opportunity it gives for forming personal character and lasting friendships. It is estimated that from 5,000 to 6,000 boys leave our public schools annually, of which not more than about 1,500 proceed

to the universities. When the country realizes how much of its capital is spent, the number of boys for whom the expensive education is possible will be fewer, whereas what this country requires is that more and more boys should be able to imbibe something of the advantages of our public schools and of the university atmosphere of Oxford and Cambridge. It may be possible so to cheapen university and even college life, that the traditions and teachings of the old universities may be available for men who cannot now afford them. Even the teaching without the college life has its advocates, and a scheme is under consideration at Cambridge by which students must be attached to a college though they reside outside and only take such part in college life as they can afford. Among the universities without resident college life it is satisfactory to know that the University of London has decided to institute degrees in commerce. The scheme has been worked out by the university authorities in collaboration with business men, and efforts are being made to raise half a million pounds sterling in order to endow the scheme adequately.

The Government has undertaken to set up commissions to inquire into the present position of both Oxford and Cambridge Universities. Relative to this inquiry the Education Committee of the Parliamentary Labour Party has asked that it may extend to a more economical utilization of university and college funds so that, by decreasing the cost of living in college, poor men with brains may have as good a chance as rich men without brains to profit from the advantages of a university career.

My excuse for venturing to touch on the vexed question of school and university education is that it is essential to this Institution, and to the industry it represents, that our systems of education shall produce men capable of electrical research. We possess a Government Department of Scientific and Industrial Research with a grant of £1,000,000 and a budget for the present year of £56,000. It is earnestly to be hoped that throughout the country our universities will qualify for substantial grants.

There is a great difference between education in this country and in the United States so far as its cost to the student is concerned. What in the States correspond to British public schools are known as preparatory schools, largely formed on our system. But the free secondary schools of the United States—their public schools—prepare and send large numbers of men to their universities where, as compared with Oxford and Cambridge, the cost is somewhere about in the ratio of dollars to pounds sterling. In this country a far greater proportion of the cost of university education is paid for by students' fees, and nine American universities have each individual incomes exceeding the sum total of the parliamentary grant to the whole of the corresponding universities and institutions in the United Kingdom. Yet before the war, although the total income per head of population was greater, the external trade (imports and exports) of the United States per head of population was less than one-third of the external trade per head in the United Kingdom.

The Chancellor of the Exchequer, speaking at the James Watt Centenary, said that university grants were to be increased. It is obvious that students' fees cannot pay for research, and without wishing in any way to urge more State endowment, with its corresponding control of our secondary education, I do wish to emphasize the fact that for our industry research is essential and that workers in research need long and specialized training. It is, I maintain, one of the duties of this Institution to see that our universities and technical schools are encouraged by suitable grants to promote original scientific research. From these trained scientific research workers must be drawn men capable of efficient industrial research. Although things are improving in one or two instances, there is little in the science-teaching in the schools from which our older universities are largely recruited, to stimulate in boys a taste for research, and for the present we must look chiefly to our State-aided secondary schools to provide research workers. Some 9,000 boys leave these schools in the United Kingdom each year, and it is estimated that about 1,000 of them pass on to one or other of our 18 universities. Every influence, individual and collective, must be exerted by the Institution to secure research students at these universities and at the technical colleges.

It is significant of the widespread understanding in the United States of the importance of research in industry, that last July the American Federation of Labour issued a manifesto on scientific research in which they called on the Federal Government to foster and support scientific and technical research as essential to the well-being and progress of industry.

The fear of government support for research in this country is the application to the research worker of those official methods of control which obtain in government departments subject to the Treasury. It is to be devoutly hoped that our research workers are not going to be turned into civil servants. The ordinary research worker can only specialize in one subject at a time, and if he successfully specialized in civil service he would lamentably degenerate in research.

Our Education Act of 1918 provides for compulsory school between the ages of 5 and 14, with the power of local authorities to increase that age to 15. Continuation schools for all not actually being educated by some other agency are compulsory up to the age of 16, and seven years hence up to the age of 18. It is not too much to say that this measure opens out profound possibilities to our race as well as to our industry, but its effect will not be felt for many years to come, and it is with the immediate demand for research workers that the Institution is now concerned.

The Wage-earner and Sportsmanship.

The war has shown that among the great assets possessed by the British race is the sporting instinct which makes men and women put the admiration for excellence of performance, for fair play and for chivalry, before the desire to win at all costs.

The expensive education, through our public school system, probably develops this instinct to its highest degree, since all executive control out of school hours is in the hands of the boys themselves with decades of

tradition behind them to lean upon. But our citizen army, whether educated or not, was as full of the sporting instinct as the German army was conspicuously without it, and I think there are ample signs in recent industrial events, not excepting the railway strike, that, in the difficult and perilous times present and to come, British common sense and the sporting instinct, if properly appealed to, will lead to a permanent working understanding between capital and labour.

But before the sportsman in the wage-earner can be appealed to, it is essential that the employer should set the example. All business is founded upon a system of profit and loss, and one of the reasons why profit-sharing schemes are unsatisfactory is that the wage-earner without capital cannot afford to lose and the system is one-sided. A man cannot be a real partner in business unless he can afford to lose. The ability to lose as well as the ability to win, is the essence of the sporting instinct, and in business the capable employer learns both as part of his daily routine. In dealing with trade unions employers do not always remember that although a delegate at the conference table may appreciate the justice of an employer's view of the men's claim, he may see no possible way of convincing those who sent him to make the claim that it is not fair. The ability to lose cheerfully is not learnt so readily in our primary as in our public schools, where it is the essence of school games, and yet sportsmanship seems always waiting to show itself if suitably encouraged.

There is no doubt that electrical engineers employing labour have been so absorbed in the past in dealing with things, and have given such an undue proportion of their time to the solving of all the material problems in connection with their work, that some of them have neglected to study the essential relationship between employer and wage-earner which is fair dealing on both sides. We are reaping the reward of this neglect, which in many cases results in the engineer now having to give all his time to dealing with people and none of it to things. Apart from any higher moral code, if in dealing with the wage-earner the employer develops his own sporting instinct to the highest possible degree and endeavours to work upon the same instinct in those with whom he deals, it is, I think, certain that with patience and time the labour problem in our industry will be solved. What the solution will be is a pure matter of speculation, but I venture to suggest that the present tendency is towards decentralization rather than the other way, and that collective bargaining for the wages of a large industry throughout the country is bound to be modified almost as soon as made through the varied interpretation of such a bargain to suit differing local conditions.

Is it too much to hope that the working of industrial councils, or if they are not adequate, some other organization of the same sort, may in due time put an end to the hundred years' industrial war in the new society which we have all to help construct?

From men and women weary of the war and overwork, impatience is to be expected, but the assumption that the mistakes of three generations can be put right in a few months is fatal to any well-considered and lasting settlement. Time and sportsmanship are on the side of common sense, and for the electrical manufacturing industry it is satisfactory that the employers' federations have been in existence for many years and are disciplined bodies. As industrial councils or their equivalent are formed, it is hoped that they will be permitted to deal with all matters of principle in the relations between employers and employed, but we must look to the working out of detail not for an entire industry, but in each individual shop through its shop committees.

It is to be feared that no system of instruction, however expensive, or however subsidized and controlled, can be expected to teach common sense. If it could, our industrial labour problems would be quickly solved. Unfortunately, some academic learning is directly opposed to common sense, and the modern habit of delegating everything requiring thought to large committees does not lead to common-sense results. Short of possessing the heaven-sent gift of common sense, which, like beauty, defies definition but is often instinctively recognized by the simple as well as by the cultured, the ability to recognize common sense in others can be acquired.

Such contact as I have had with my fellow countrymen generally, and with the wage-earner in particular, has convinced me recently, as it has convinced many far better qualified to judge, that the gift of common sense is much more general than I once thought it to be. If I am right, we have not much to fear. Its great enemy is personal vanity, and the possession of personal vanity in either employer or wage-earner, or often in both, is a very frequent obstacle to the settlement of disputes, as well as the prime cause of most of them.

The Work of the Institution.

In his Address two years ago * the retiring President outlined a comprehensive programme for the work of the Institution, and early last year he reported progress to the territorial centres.† Although, in spite of the many handicaps to accomplishment, much of that programme has been carried out, there remains more than enough still requiring discussion and consideration in the present session.

Conditions are so changing; the expectation of rapid industrial expansion after the signing of Peace has been so little realized; the problems of reconstruction are so many and so conflicting; and the provisions of the Electricity Bill should it become an Act are so far-reaching, that the Institution must be in a position to defer any part of its programme not intimately bound up with any or all of these considerations, and be ready to give its whole energies to meeting each circumstance as it arises.

Brief reference must, however, be made to one or two items in the 1918 programme, which may form a necessary or important part of reconstruction.

British Engineering Standards and Electrical Proving House.

The question of an Electrical Proving House has been fully discussed within the Institution. It is to be hoped

* *Journal I.E.E.*, 1918, vol. 56, p. 1.
† *Ibid.*, 1919, vol. 57, p. 338.

that manufacturers and traders in our industry will discuss it as a business proposal. I do not think too sanguine a view can be taken of the importance, both to our home and our foreign trade, of the standard specifications of the British Engineering Standards Association. Reproduced in several languages, they form, for such sections of engineering work as are at present dealt with, standards which, if complied with, are a hall-mark of British material or performance. But it must always be clearly realized that no force other than goodwill stands behind these standards to compel their acceptance, and they have mercifully been preserved from the attentions of D.O.R.A. In their framing manufacturers and users alike take part, but no specification or standard is issued unless the manufacturers both desire and approve of it, and it rests with the manufacturers not only to comply with the standard specifications when the users ask for it, but to educate the public to demand British standard materials or articles, not only in the British Isles but in the Dominions and in foreign countries.

It is this education of the user, by manufacturers and their agents, to realize that it is to their advantage to ask for a British standard article rather than one that is not standard, which is one of the really important matters of reconstruction, and in no industry is it more important than in the electrical industry, because the work of the International Electrotechnical Commission which we welcomed in London last month, has already secured a large measure of international agreement in fundamental electrical standards upon which national standard specifications have been and are being founded.

Obviously by the time this education of the public bears fruit, it will be a great advantage to have a Proving House to say authoritatively if materials or manufactured articles comply with the British Standards or not. It is conceivable that the Proving House might in time extend its functions to testing and certifying that materials or articles comply with electrical engineers' specifications, but unless, as in so many previous cases, there is to be waste of time, money and energy, due to an attempt to make the functions of this new body overlap those of other existing bodies, and to launch out, as has been suggested, into scientific research, technical education, and the work of the consulting engineer, its duties must to begin with be strictly and rigidly confined to certifying compliance or otherwise with the standards and specifications of the Electrical Section of the British Engineering Standards Association.

It is too early to consider how far the views just expressed are in agreement with those of the Government, but it will be of interest to repeat here an extract from the proposals and decisions of the Government issued by the Prime Minister on the 22nd August last :—

> *Standardization.*—"There is growing recognition of the importance for the future of British industry of the principle and practice of standardization, but so far the State has done little. It is proposed to set up at the Board of Trade a Department of Standards, (1) to promote and co-ordinate standardization generally, and (2) to establish and administer such testing institutions as may be found necessary, and authorize and, so far as may be required, supervise the testing work carried out by technical institutions, trade organizations, or private concerns."

Patent Law.

Another matter affecting our industry very closely is the Patent Law. Before last year's government Patent Bill was dropped, the adoption by most of the interested bodies of the report drawn up by the Institution Committee under the chairmanship of Mr. Mordey, enabled the patentees' case to be put before the Board of Trade with great force. In the Bill now before Parliament which passed the House of Commons before the recess, but still awaits its passage through the House of Lords, it is to be regretted that the conclusions of this Committee have not been embodied. Before the 1919 Bill becomes an Act it is to be hoped that some of the disabilities under which the genuine inventor has laboured in the past will have been removed by amendments.

Sister Institutions.

As an example of the Institution's co-operation with other bodies, a passing reference may be made to the Institution's share in the formation of the new Society of Radiographers for securing the efficient training and registration of lay helpers in radiography. This Society, as already referred to by our retiring President in his Address to the Territorial Centres, has been formed in happy conjunction with the British Association of Radiography and Physio-therapy.

It is gratifying to learn that arrangements have been made by the medical profession for the granting of a diploma by Cambridge University in the subjects of Radiology and Electrology for medical men engaged in this class of work. It is hoped eventually to develop an educational scheme in teaching centres throughout the country, as well as in the chief hospitals, in order to train men for this diploma. In this way it is intended to raise the status of medical men practising these branches of medicine in which electrical science plays an important part.

I hope this method of co-operation, in which each body does its own work without overlapping, may form a precedent for co-operation in the imperially important matter of our relations with engineering societies in the Dominions and in India. Trustworthy prophets predict great industrial developments in Canada within the next 10 years in which electricity will play a large part, and if from natural causes similar developments in South Africa, Australia, and New Zealand are neither on so great a scale nor so rapid, each Dominion will soon be creating its own technical societies. I hope when that time comes this Institution will hold out the right hand of fellowship and help our younger sister nations in every possible way.

In India an excellent beginning has been made. As a result of the report of the Indian Industries Commission early this year, the Indian Society of Engineers was formed to include all branches of the profession. At its inauguration it was promised, and has since received, the support of the Indian Government, and the Public

Works Department supply a large number of its members. This Institution is represented on the Organizing Committee by its Honorary Secretary in India and by an ordinary member. The first meeting will, I understand, be held at Delhi some time in December of this year under the Viceroy's presidency, and we wish all success to the new Society, hoping that this Institution will never lose touch with its electrical members, and that when the Indian Society of Engineers has settled down, many ways may be found by which our Council may assist its electrical members from this side in various directions that may advance the profession in both countries.

The Institution is to be congratulated on the formation last session of a Wireless Sectional Meetings Committee to deal with radio-telegraphic and high-frequency engineering. Although the Committee only met for the first time in the middle of last February, three important papers by soldiers who had largely helped in the development of wireless during the war were read during last session.

The Railway Electrical Engineer.

The new conditions arising from the Ministry of Transport Act and the Electricity Bill, when it becomes an Act, obviously affect the use of electricity by railways, both for traction, for power, and for lighting.

Electrical development on railways there is bound to be, not only on account of its advantages, but because the use of electricity for many purposes is becoming the fashion. Should the amount of electrical engineering carried out by the railways increase considerably, it is of importance to everybody that such work should be carried out and maintained by electrical engineers of standing in the profession.

Electric traction, and the application of electrical machinery to all sorts of railway requirements and the handling of goods at ports and in goods stations and yards, are still largely pioneer work requiring a sound engineering training and a high order of mental attainment. No engineer ought to be responsible in fact for carrying out work involving many hundreds of thousands or even millions of pounds, unless he is also responsible in title.

The construction of railways by the civil engineer, and their equipment by the mechanical engineer, have been carried out by men standing high in their profession, to whom the spending of large sums of money and the design of the work could be safely entrusted. This has become a railway tradition, and unless that tradition is to be broken in electrical engineering, the work ought not to be wholly designed and carried out either by a consulting engineer or by the designing staff of a selected contractor.

Railway electric traction and the design of electrical machinery for dealing with goods and goods wagons require as much skill and training as any work falling to the lot of the electrical engineer. If therefore the railway engineering tradition is to be continued the man responsible for the design and maintenance of railway electrical work must be a first-class man, and no first-class man will long be content to be a subordinate in another department. It is to be hoped that every railway carrying out important electrification schemes will, if it has not done so already, create an electrical department for the purpose.

Railway Structure Gauge.

Sir John Aspinall a year ago in his address as President of the Institution of Civil Engineers expressed the view that the pressing question to be faced on British railways was that of the increase in the structure gauge.

The structure gauge determines the loading gauge which fixes the greatest cross-section of the rolling stock and anything it may carry. Sir John pointed out that there are 66 different loading gauges on British railways.

Since without increase in our structure gauge foreign rolling stock could not run over our railways, and that our limited and various structure gauges were the main difficulty in the way of improvement in all sorts of directions making for economy in transport and in the standardization of rolling stock including locomotives, Sir John Aspinall urged that it was a national matter and that the structure gauge should be increased throughout the country at the national cost.

Should this matter be undertaken by the Ministry of Transport it is hoped that provision for the overhead equipment of railways for electric traction will not be overlooked. The various considerations urged by Sir John Aspinall for increasing the structure gauge may not essentially apply to an increase in height. But low overhead structures—tunnels, bridges, station roofs and the like—have always hampered the fixing of overhead electric conductors for traction and it is important in considering the general case that this should not be left out.

Strength of Draw Gear and Traders' Wagons.

The electrification of railways crossing mountain ranges in the United States and elsewhere have shown the ability of the electric locomotive to haul heavier mineral and goods trains up grades at higher speeds and with fewer locomotives than with the steam locomotive.

In this connection a matter of great importance is the decision under the Ministry of Transport Act to acquire traders' wagons, which roughly form half of the 1,250,000 wagons in use on our railways. Privately owned wagons, of which it is estimated that 90 per cent are coal wagons of from 10 to 12 tons' capacity, are built to a specification issued by the Railway Clearing House. Draw gear is supposed to be tested to 50 tons and to be worked at 12½ tons and to be maintained at that strength, but the frequent breaking of couplings at much lower draw-bar pulls show that this is not done.

If heavier goods trains and especially mineral trains are to be hauled by electric locomotives at increased speeds, the strength of the draw gear on all wagons must be increased, and maintained at that increased strength, while continuous brakes must be fitted to the fast mineral trains, which is obviously not a requirement that could have been imposed on the trader owners.

Within the limitations of the present structure gauges and the strength of bridges the greatest dimen-

sions of the steam locomotive which determine hauling capacity have been reached, but that capacity on at least one railway amounts on the level to a 1,600-ton load (inclusive of wagon weight) at a high speed. If consisting of 10- or 12-ton wagons such a load would be formed by about 100 wagons and the train exceed one-third of a mile in length. Should the structure gauge be increased, the power of the steam locomotive could also be increased and the limitation of weight of train which could be hauled would be more emphatically than it is now the strength of the wagon draw gear and not the capacity of the steam locomotive, which has only reached its limit on gradients.

There is a further limitation to the maximum length of mineral or goods train which can be hauled in the length of lay-by and reception sidings. Many of these are made for only 60 or at most 80 wagons, and it is earnestly to be hoped that in laying out new reception sidings and especially "hump yards," where the sorting of wagons is done by gravity, the importance of accommodating trains of at least 100 wagons or more in length will be recognized, if the electrification of goods lines is to be profitable.

Only some of the conditions at present limiting the use of long and heavy goods and mineral trains at high speeds have been briefly stated. Small-capacity coal wagons limit the train load very greatly, but where wagons have to pass under a coal screen in order to load, very few collieries in the country have screens high enough to take more than the 10- or 12-ton wagon.

Enough has been said to suggest that in this country, unlike the United States, many things have to be changed before electric traction can assert its full advantage in hauling heavier goods trains, though increased speeds could be obtained at once. And these changes will take years to carry out.

Economics of Railway Electric Traction.

If, then, mineral and goods traffic is to be hauled electrically under present conditions of size of wagon, strength of draw gear and capacity of sidings, it must be because it is more economical in the cost of haulage, and the same applies to passenger traffic which is without these limitations.

There is, however, an exception to be made to the above statement in the case of mineral traffic down valleys where gradients are steep. This is the case of the Shildon and Newport mineral line electrified by the North-Eastern Railway.

In such cases the maximum hauling capacity of the steam locomotive is not sufficient since the train of full wagons which came down the grade may have to be divided into two or even three trains of empties before these can be taken up the grade. The saving in locomotives, in locomotive crews, and in time far exceeds any saving in cost of haulage, and railways may confidently embark on the electrification of mineral lines with steep gradients even when electricity is not cheap.

The steam locomotive which can haul 1,600 tons on the level cannot haul one-third of this load up a gradient of 1 in 50 at a convenient speed, while within the same load gauge an electric locomotive can be made to haul the 1,600 tons up 1 in 50, or if need be double this load, provided the draw gear is strong enough.

Electrical engineers, and others, not engaged on railways are at times liable to forget that railways are not run by the engineering but by the traffic department. The traffic department has gradually built up its requirements to suit the needs of the travelling public and the trader, and it is those requirements that the engineer has to meet.

In many directions electric traction provides entirely new possibilities which the traffic department has yet fully to realize. To make use of these new methods the traffic department has first to adapt its ideas and habits to the changed conditions and next to carry the travelling public and the trader with it. No small measure of imagination is required by a railwayman to grasp quite new conditions of service and to do so with the enthusiasm of the propagandist.

Main Line Electrification.

In discussing the economies of electric traction on railways I propose to consider only the locomotive and the train it hauls, to analyse its running costs with steam and to see if electricity can introduce such economies in working costs as to warrant its use. Until the new possibilities with electric traction are understood and gradually adopted no appreciable alteration to traffic costs is to be expected, and in the following analysis traffic costs will be taken as unaltered.

Consider the question of superseding the steam locomotive by the electric locomotive both for passenger and for goods services throughout the railways of Great Britain.

When supplied by electricity from central stations using modern large turbo-alternators enjoying such diversity of load that the power factor is above 30 per cent, the coal burnt in the furnaces of the boilers to produce a given hauling effect on the railway by means of an electric locomotive is at most 40 per cent of the coal burnt in the furnace of a steam locomotive to achieve the same result. To a nation which has largely paid for its imported food by its exported coal and has built up all its manufactures and most of its trade on the foundation of cheap coal, I need not remind you, now that coal has ceased to be cheap, how important the saving on the railways of between 7 and 8 million tons of coal each year would be could it be achieved.

It has been roughly estimated that to electrify all the railways in Great Britain would cost some £300,000,000, and if coal ever rose to 45s. per ton the saving of 7,000,000 tons per annum would of itself pay 5 per cent on the investment.

The last statistics published by the railways under the Railway Accounts and Returns Act 1911 were for 1913. If in these returns the working costs per steam locomotive are compared for several large railways running more than 12,000 passenger, goods and mineral train-miles for each mile of route over which the locomotives of each railway work, it is found that these costs are very similar. Average costs for one typical main-line railway are therefore a rough indication of the costs for the others. They may, however, be quite mis-

leading for railways whose traffic is mainly passenger or for railways where goods or mineral traffic largely predominate.

The figures in the analysis which follows have little intrinsic value in themselves but indicate tendencies, and that is all that is claimed for them.

On the typical railway chosen there are roughly 50 per cent more passenger-train miles than goods-train miles run and twice as many goods locomotives as passenger locomotives used to run them.

The cost of running a passenger locomotive in 1913 averaged over the year and the railway was £1,240. Of this amount superintendence; lubricants, small stores and miscellaneous; repairs, renewals and depreciation; together with interest at 5 per cent on the cost of the locomotive amounted to £780 and coal and water to £460, which is 37½ per cent of the whole.

The average number of passenger-train miles hauled by each locomotive per annum was 27,000 and the cost per train-mile for coal and water was 4d. and for the other items 7d., making a total per train-mile of 11d.

The cost of running a goods locomotive in 1913 averaged over the year and the railway was £1,020. Of this amount superintendence; lubricants, small stores and miscellaneous; repairs, renewals and depreciation; together with interest at 5 per cent on the cost of the locomotive amounted to £770 and coal and water to £250, which is 24½ per cent of the whole.

The average number of goods-train miles hauled by each locomotive per annum was 10,000, and the cost per train-mile for coal and water was 6d. and for the other items 1s. 7d., making a total per train-mile of 2s. 0½d.

During the present year the cost of coal has increased by 148 per cent, and all the other items making up the working costs, except interest, have been increased by percentages ranging from 120 to 212, so that now the working cost of the train-mile for passenger service is 2s. 0d. and the working cost of the train-mile for goods and mineral service is 4s. 8d.

Experience in America and elsewhere has shown that the annual passenger-train miles per locomotive would be increased from 27,000 with steam to at least 40,000 with electricity, and the annual goods-train miles per locomotive would be increased from 10,000 to at least 20,000. Taking these minimum increases and assuming also that the total of all the working costs other than coal and water were the same as for steam, which is not in favour of the electric locomotive, these items come to 10d. for the electric locomotive passenger-train mile and to 1s. 8d. per electric locomotive goods-train mile.

Subtracting these costs from the total steam-train mile costs of 2s. 0d. and 4s. 8d. respectively for passenger and goods service, there is left, per electric locomotive train-mile, 1s. 2d. for passenger service and 3s. 0d. for goods service to pay for electricity and also to pay interest on the cost of the electric locomotives and of the electrical equipment—substations, the track conductors, section switches and bonding of the rails.

Considering first the interest on the capital required for electrical equipment, Mr. F. W. Carter in a recent communication to the Press * estimates that with high-pressure direct-current equipment the cost of electrifying a railway where, as in Great Britain, there is on the average one steam locomotive per mile of route (which is the case for the type of railway considered) is approximately double the cost of the electric locomotives required. He also states that the cost of an electric locomotive is 2½ times the cost of the steam locomotive for equal draw-bar pull and speed.

The average capital cost this year of a steam locomotive may be taken as £7,000, so that for each electric locomotive required on the railway its capital cost, together with that of the electrical equipment of the line exclusive of power house and high-pressure transmission, will to-day be some £35,000.

In that figure no credit has been taken for displaced steam locomotives, nor on the other hand does it include anything for structural alterations which it has been already urged should be made at the cost of the State since much larger interests than electrification are involved.

If the revenue earned by the train mileage hauled by each electric locomotive has to pay interest at 5 per cent on the capital cost of the equipment, then each passenger locomotive hauling 40,000 train-miles per annum must earn 10½d. per train-mile and each goods locomotive hauling 20,000 train-miles per annum must earn 1s. 9d. per train-mile to pay interest on electrical equipment including locomotives.

The earnings for both interest and electricity were per passenger-train mile 1s. 2d. and per goods-train mile 3s., consequently each passenger electric locomotive has 3½d. and each goods electric locomotive has 1s. 9d. left per train-mile for electricity.

I shall show later on that where in this country railways generate their own electricity the annual one-hour load factor (i.e. the maximum load averaged over one hour) does not exceed 40 per cent except in one special and unique instance. If, however, railways can obtain electricity from power stations with great diversity of load reaching a maximum value of not less than 50,000 kw., it may be possible to generate with a load factor of about 50 per cent, and under these conditions even at recent prices electricity for traction should be able to be bought for ½d. per kw.-hour at the generating station.

At this price the 3½d. and 1s. 3d. available respectively per passenger and goods electric locomotive will provide 7 kw.-hours per passenger-train mile and 30 kw.-hours per goods-train mile.

Assuming 40 watt-hours per ton-mile as an average for passenger service, the average weight of passenger train including the locomotive would be only 175 tons.

Assuming 30 watt-hours per ton-mile as an average for goods service, the average weight of goods train including the locomotive would be 1,000 tons.

The assumptions made in this analysis are numerous and doubtless controversial, but for the type of railway taken they are the same for the passenger and for the goods electric locomotive with the exception of the annual train-miles worked, for which we must go abroad for

* F. W. Carter: "Electrification of British Railways," *Electrical Review* 1919, vol. 85, pp. 68 and 121.

our figures. It is for the traffic department to say what average weight of train would be required to be hauled by an electric locomotive, but in order to earn the present revenue per train-mile the average passenger train including its locomotive should be more nearly 275 than 175 tons, while the goods train of 1,000 tons is of course much heavier than is hauled in this country as an average.

It has been already pointed out that this analysis only indicates tendencies, but I think it may be claimed that basing the working costs of each kind of locomotive, steam and electric, on the average train-miles hauled in a year, and placing the known increase in train-miles hauled by an electric locomotive at reasonable figures for passenger and goods respectively, the passenger electric locomotive might have difficulty in earning sufficient revenue to meet all present charges and have enough to spare to pay for electricity and for interest on the electrical equipment, while the goods locomotive could much more than do so, provided in both cases electricity is bought or produced by the railway at ½d. per kw.-hour at the generating station. I must, however, insist once more that in an analysis of this sort the actual conclusion come to, which is in the form of the weight of passenger train and of goods train (including the locomotive) that can be hauled for the same working expenses now necessary for steam traction, has no intrinsic value and if applied to any individual case might be most misleading. All that the figures show is that in a typical case for the same working expenses now incurred by steam traction, electrification is more in favour of goods haulage than of passenger haulage, and among the railway economies necessary to pay the enormously increased working expenses the electrification of goods and especially of mineral lines ought to receive due consideration.

Present Use of Electricity by British Railways.

With the exception of the 18 route miles of mineral line already referred to between Shildon and Newport which has been electrified by the North-Eastern Railway with great success, all the electrified railways in this country are of the suburban type in that they are worked on the multiple-unit system, each unit consisting of a motor coach hauling or pushing one, two or three trailers, these units being made up into trains of any length required to suit the traffic conditions, capable of being driven from either end whatever the formation may be.

The feature of all suburban electrification replacing existing steam haulage has been first to restore a decreasing traffic, in cases where it had decreased, and then to increase the traffic. Figures for several such cases have been published and I only propose to add some particulars given me by Sir Herbert Walker for the London and South-Western electrified suburban system. The length of route electrified is 49 miles and the length of single track is 152 miles.

A diagram showing the number of passengers carried during seven 12-monthly periods will be found on page 10. I here propose to summarize the figures. Between 1913 and 1915 the total number of passengers carried annually by steam trains fell from 25,000,000 to 23,300,000, or 7 per cent. The first electrified section started in October 1915 and the number of passengers carried in 1916 showed an increase of 26 per cent over the previous year. In 1917, when the programme of electrification was complete, the number of passengers carried showed an increase of 41 per cent over 1915, and during 1918 an increase of 73 per cent over 1915. The passengers carried last year amounted to over 40,000,000 with a car mileage of 5 per cent less than in the previous year. During this year so far the 1913 figures have been more than doubled.

The L. & S.W. Railway electrification has proved satisfactory not only in averting and restoring a diminishing traffic but, assisted by war conditions, has been used to its utmost capacity and proved a most valuable additional facility for the Government in meeting the restrictions placed on road motor traffic.

In Great Britain at the end of 1918, as at present, there were 351 miles of railway route electrified, equivalent, with sidings, to 834 miles of single track. By the courtesy of the General Managers of fourteen of the leading British railways using electricity for traction, lighting, and power, I am able to give the total amount of electricity used for such purposes by these railways during last year. A table of these totals will be found on page 11.

Also through the good offices of Mr. H. M. Hobart and the public-spirited energy of Mr. Oehler, one of the Associate Editors of the New York *Railway Age*, I am able to give you similar figures for eight of the railways in the United States.

The information may be taken as fairly representative, but unlike that given for British railways it is very far from being complete. Moreover, it includes no underground railways. Six out of the eight railroads are trunk lines where the majority of the traffic is hauled by steam locomotives and about half of the 2,762 miles of single track for which figures are given is main-line electrification.

For the eight railways in question during 1918 the electricity used for traction was 478,000,000 kw.-hours with an annual one-hour load factor of 46 per cent. Almost exactly half of this electricity was bought at an annual one-hour load factor of 49 per cent, while that generated by the railways had a load factor of 42 per cent.

For lighting and power 164,000,000 kw.-hours were generated and bought at an annual one-hour load factor of 44 per cent.

It will be noticed that in every instance the load factor is better than on British railways, being above rather than below 40 per cent.

Sixty-eight American railways possess 760 workshops, two-fifths of which generate their own electricity for power, and a total of 366,500 h.p. is connected to the supply.

The Institution will, I know, appreciate the kindly feeling which allows of the publication of these few details.

On the 14 British railways, which possess all the electric traction and by far the greater part of the use of electricity for other purposes in this country, the total kilowatt-hours used during 1918 for traction were 400,000,000 and the kilowatts of maximum demand

averaged over an hour were 123,000. Consequently the annual one-hour load factor was 37 per cent. Ninety per cent of the electricity was generated by the railways at an annual one-hour load factor of 41 per cent. The remaining 10 per cent of the electricity was bought and from the figures of maximum demand given, which are generally difficult to estimate, the load factor is 19 per cent.

The important point is that for suburban services, many of them continuous for 20 hours or more, the greatest annual load factor which has been obtained in this country when railways generate their own electric power is about 40 per cent. It is probable that the electricity bought had about the same load factor.

The load factor for the electricity used for lighting and power is referred to later in its proper place. The total use of electricity by the 14 railways for traction, lighting, and power in 1918 amounted to 517,000,000 kw.-hours and the annual one-hour load factor was 34 per cent.

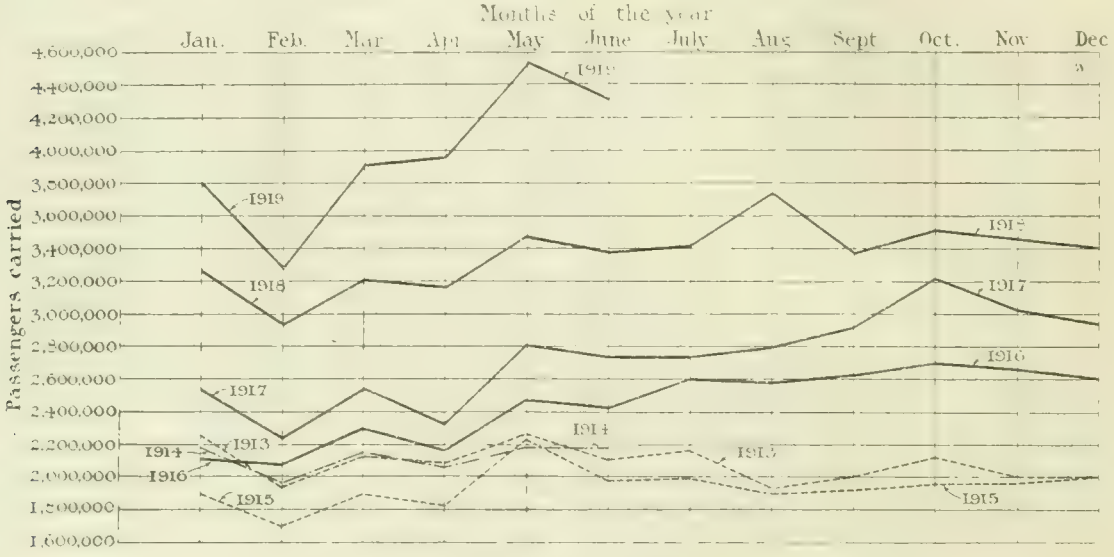
When the war started, British railways were actually committed to the carrying out of additional electric traction and with it a certain amount of power and lighting which was stopped by the war. Had this work been carried out the estimated kilowatt-hours of electricity generated would have been 357,000,000 at an estimated load factor of 43 per cent.

But for the war the total electricity generated and bought by the 14 railways during 1918, including these commitments, would have been 875,000,000 kw.-hours at an annual one-hour load factor of 37 per cent.

For 1918 no complete returns of the electricity sold by public supply authorities in the United Kingdom are available. In 1914 it was 2,100,000,000 kw.-hours and in 1917 3,520,000,000 kw.-hours.* It has been estimated at 4,200,000,000 kw.-hours in 1918, it being of course understood that this figure is only for supply authorities and is exclusive of the quantities privately generated.

The 14 railways therefore actually used for all purposes in 1918 12¼ per cent of the quantity generated by supply authorities, and would have used 20 per cent taking account of such part of it as would have been bought, supposing their actual commitments had not been stopped by the war.

Apart from the importance of the present railway load as compared with the whole load of the supply authorities, a proportion which is quite certain to in-



London and South-Western Railway.

Number of passengers (including season-ticket holders) travelling on the suburban electrified system, exclusive of those travelling only between Waterloo and the City.

Year	Passengers	Car Mileage
1913 Steam	25,011,569	—
1915 Steam until October 25th, when Wimbledon section started	23,301,236	—
1916 Electrification nearly complete	29,361,917	12,355,404
1917 Electrification complete	32,869,316	16,089,563
1918 Electrification complete	40,376,731	15,452,352

* *Journal I.E.E.*, 1919, vol. 57, p. 409.

crease as soon as railway policy is defined, I have insisted on quoting a number of figures including load factors because there has been a tendency in some quarters to exaggerate the value of the railway load factor, which it will be seen both in actual fact and in estimate is in this country below 40 per cent for the densest type of suburban service. The highest railway traction annual one-hour load factor in this country for one of the most dense electric services in the world—the London tube service—reaches 48 per cent and is the same for traction as for lighting and power. But this value is altogether exceptional.

USE OF ELECTRICITY BY 14 LEADING BRITISH RAILWAYS FOR TRACTION, LIGHTING AND POWER DURING 1918.

Traction on 10 Railways.

Length of electrically equipped route, miles	351
Equivalent length (including sidings) of single track, miles	834
Electricity generated by railways, kw.-hours	360,171,100
Maximum demand averaged over one hour (one-hour demand), kw.d. ..	99,380
Annual one-hour load factor, per cent ..	41·5
Electricity bought by railways, kw.-hours..	39,076,000
Maximum one-hour demand, kw.d. ..	23,450
Annual one-hour load factor, per cent ..	19
Total use of electricity for traction by 10 railways, kw.-hours	399,247,100
Maximum one-hour demand, kw.d. ..	122,830
Annual one-hour load factor, per cent ..	37

Lighting and Power on 14 Railways.

Electricity generated by railways, kw.-hours	83,760,900
Maximum one-hour demand, kw.d. ..	30,300
Annual one-hour load factor, per cent ..	32
Electricity bought by railways, kw.-hours..	33,893,130
Maximum one-hour demand, kw.d. ..	21,530
Annual one-hour load factor, per cent ..	18
Total use of electricity for lighting and power, kw.-hours	117,654,030
Maximum one-hour demand, kw.d. ..	51,730
Annual one-hour load factor, per cent ..	26

Total Use of Electricity on 14 Railways for Traction, Lighting and Power.

Electricity generated and bought, kw.-hours	516,901,130
Maximum one-hour demand, kw.d. ..	174,560
Annual one-hour load factor, per cent ..	34

Additional Commitments for Traction, Lighting and Power to have been carried out but for the War.

Electricity generated and bought by eight railways, kw.-hours	357,564,980
Maximum one-hour demand, kw.d. ..	95,190
Annual one-hour load factor, per cent ..	43

Total Use of Electricity on 14 Railways for Traction, Lighting and Power inclusive of Actual Commitments to have been carried out but for the War.

Electricity generated and bought by 14 railways, kw.-hours	874,466,110
Maximum one-hour demand, kw.d. ..	269,750
Annual one-hour load factor, per cent ..	37

Seven Railways with Traction in Greater London.

Length of electrically equipped route, miles	211
Equivalent length (including sidings) of single track, miles	556
Electricity generated and bought for traction, kw.-hours	340,247,160
Maximum one-hour demand, kw.d. ..	100,340
Annual one-hour load factor, per cent ..	38·5
Electricity generated and bought for lighting and power, kw.-hours	52,459,780
Maximum one-hour demand, kw.d. ..	20,720
Annual one-hour load factor, per cent ..	29
Total use of electricity for traction, lighting and power, kw.-hours	392,706,940
Maximum one-hour demand, kw.d. ..	121,060
Annual one-hour load factor, per cent ..	37

Additional Commitments for Traction, Lighting and Power to have been carried out but for the War.

Electricity generated and bought by seven railways, kw.-hours	247,564,980
Maximum one-hour demand, kw.d. ..	75,190
Annual one-hour load factor, per cent ..	37·5

Total Use of Electricity by 14 British Railways for Traction, Lighting and Power, including Actual Commitments to have been carried out but for the War.

Electricity generated and bought by 14 railways, kw.-hours	874,466,110
Maximum one-hour demand, kw.d. ..	269,750
Annual one-hour load factor, per cent ..	37

USE OF ELECTRICITY FOR EIGHT RAILROADS IN THE UNITED STATES FOR TRACTION, LIGHTING AND POWER DURING 1918.

Traction on Six Railroads. Four of them Steam Trunk Lines with some Electric Traction.

Length of electrically equipped route, miles	1,413
Equivalent length of single track, miles ..	2,762
Electricity generated by railroads, kw.-hours	237,732,125
Maximum one-hour demand, kw.d. ..	63,630
Annual one-hour load factor, per cent ..	42
Electricity bought by railroads, kw.-hours..	239,847,678
Maximum one-hour demand, kw.d. ..	55,150
Annual one-hour load factor, per cent ..	49
Total use of electricity for traction by six railroads, kw.-hours	477,579,803
Maximum one-hour demand, kw.d. ..	118,780
Annual one-hour load factor, per cent ..	46

Lighting and Power on Eight Railroads.

Electricity generated by railroads, kw.-hours	105,763,924
Maximum one-hour demand, kw.d. ..	28,650
Annual one-hour load factor, per cent ..	42
Electricity bought by railroads, kw.-hours..	58,024,000
Maximum one-hour demand, kw.d. ..	14,445
Annual one-hour load factor, per cent ..	46
Total use of electricity for lighting and power, kw.-hours	163,787,924
Maximum one-hour demand, kw.d. ..	43,005
Annual one-hour load factor, per cent ..	44

Total Use of Electricity on Eight Railroads for Traction, Lighting and Power.

Electricity generated and bought, kw.-hours	641,367,727
Maximum one-hour demand, kw.d. ..	161,785
Annual one-hour load factor, per cent ..	45

Diversity of many loads, of fairly good but different load factors, from one or more interconnected power stations where the individual units can be of greater output than would be possible in a power station devoted almost entirely to traction, will do more to cheapen electricity than the separate generating station for each railway. In London this result could have been achieved in the past by supplying the electrical needs of several railways from one station, but railway legislation made this quite impossible. So far as cheap electricity is concerned it would be an advantage for railways to be able to obtain electricity from power stations with diversity of load, generated by units of power large enough to reduce the capital invested to the lowest possible figure, since capital costs are half the generating costs and large turbo-generators are more economical than small ones.

But essential as cheap electricity is for railway electric traction, a cheap supply is only one and possibly not the most important requirement.

The locomotive working costs of a steam railway such as has been taken as typical when comparing passenger with goods and mineral working is one-third of the total traffic expenditure incurred in working the railway including locomotive repairs, maintenance and depreciation, and, of this third, coal and water which were in 1913 one-third now amount to about two-fifths. Roughly, electricity corresponds to and replaces steam-locomotive coal and water in cost, so that for main-line electrification electricity will figure as something of the order of 13 to 15 per cent of the total traffic costs of running the railway.

To the railway what is of greater importance than the cost of electricity is security of supply, and the policy of the railway companies in building their own power stations and in wishing to keep those that they have built is chiefly for security of supply.

Railways work under statutory obligations, and before they depend on others than themselves for their supply of tractive power they must be sure that the supply will always be available, in the quantities they require at any moment, and in case of curtailment of supply, that the railway has the first consideration.

For railways taking a supply from other power stations than their own the geographical position of the latter relative to the railway is a matter of importance from the point of view of cost. The working-pressure transmission of a main-line railway is necessarily long and if, in addition, the substations are a long way from the power stations one of the advantages in cost of supply of the large common power stations may be lost in the transmission. Knowing that the capital charges form at least 50 per cent of the cost of electricity, railways, like everyone else, are anxious to use stations equipped with the largest possible units of power so that the capital cost may be a minimum. In a recent paper Mr. J. S. Highfield * gave an analysis of present-day costs of stations and of generation which shows that a difference of £18 in the capital cost per kilowatt of load in favour of a station capable of supplying 50,000 kw. above a station capable of supplying only 6,000 kw. of load was all wiped out by the cheapest possible high-pressure transmission at 33,000 volts in a distance of 15 miles with underground cables and in a distance of 30 miles with overhead cables.

The great capital cost of high-pressure transmission, coupled with the need for security, is the principal reason why railways have in the past preferred stations on their own property in spite of the disadvantages of smaller units of power and hence higher capital and working charges than in large common power stations.

I hope, however, that the working of the Electricity Act when it is passed may result in railways reaping the advantage of supplies from stations of low capital cost per kilowatt, possessing considerable diversity of load, so situated that they may be able to supply electricity cheaply at the substations, and so worked that the railway may have security of supply.

High-pressure Direct-current Electricity for Traction.

We have in this country examples both of high-pressure direct-current electric traction and of high-pressure single-phase electric traction. Both have been successful, and it is quite possible that under certain conditions as great economy may be obtained by the use of single-phase current provided that a single-phase supply is obtainable at a price which compensates for the higher efficiency and less cost of the direct-current motor on the train, and the increased losses in the return through the rails with alternating current. But in a majority of cases where economy was a first consideration careful estimates of both single-phase and high- or low-pressure direct-current traction have shown capital and working costs so decidedly in favour of direct current that those responsible for the expenditure had no hesitation in adopting the latter system.

Whether the railways are worked as a whole or as separate concerns, if main-line electrification is to be carried out it is necessary that an electric locomotive should work anywhere, and it is certainly desirable that one system should be adopted for the whole country for main line as apart from suburban traction. So far as our present knowledge goes the railways of the whole country would be more economically electrified by direct current than by alternating current.

The Ministry of Transport will doubtless review the whole situation before coming to a decision, but for the purposes of this address I propose to assume that any main-line electrification will be by means of high-pressure direct current.

Although there are instances to the contrary in Great Britain, it may be stated as a general rule for suburban service that it is not worth while to electrify for a service to be run by multiple-unit rolling stock unless a pair of tracks can be set apart wholly for the service.

* J. S. Highfield: "The Supply of Electricity," *Journal of the Royal Society of Arts*, 1919, vol. 67, p. 408.

This condition obtains on a majority of the main-line railways which have suburban electric services and on one of them, where the suburban electric service interferes with the main line, a scheme is ready for extensive alterations to ensure the isolation of the suburban tracks. In general it is fair to assume that whatever system or voltage is in use for suburban services, this will not interfere at all or only to a limited extent with main-line electrification.

At present there is no need to fix a standard pressure or pressures for direct-current main-line working, nor has the matter yet been sufficiently discussed. Presently it will have to be fixed, but nothing has yet been done in the way of railway electrification which anticipates a decision or will prevent it being decided entirely on its merits. On their Manchester and Bury line the Lancashire and Yorkshire Railway have shown that the protected third rail designed by Sir John Aspinall can be used most successfully at 1,200 volts, and it is equally certain that, perhaps with some modification, it will be as successful at 1,500 volts. There are many places where overhead conductors are not desirable and others where they are not possible, and should this type of protected third rail be acceptable the maximum pressure at which it can be run will form the, or one, standard voltage.

The fullest consideration will then have to be given as to whether a pressure of, say, 1,500 volts is high enough for main-line electrification or if double this pressure will be needed for overhead equipment. Fortunately this decision will not have to be taken in a hurry, but if two pressures have to be used for main-line electrification, locomotives must be able to use both.

Suppose that a dozen contactors are wanted to control each pair of high-pressure direct-current motors at the lower pressure, then to enable the locomotives to work also at double this pressure some 30 contactors may be required.

Speed control by shunting the field goes far to remove perhaps the only disadvantage of the series motor, namely, that it has only one speed for each load. In favourable cases field control may reduce rheostatic losses during acceleration by as much as 50 per cent, and the additional running speeds obtainable are essential for main-line working.

The economy over the wearing away of wheel tyres and brake shoes by turning the series electric motor into a shunt-wound generator and returning a part of the energy otherwise lost in braking to the line by regenerative electric braking, is so obvious that it must always appeal to the engineer in spite of its difficulties. If it is required, then more contactors are needed, and should it be necessary to run a locomotive at two direct-current pressures one double the other, to employ shunt field regulation and to have regenerative braking, the 12 original contactors may be multiplied by four at least to give the necessary changes in the connections.

The cost and maintenance of so large a number of contactors becomes a serious item, and until considerable experience has been obtained in their manufacture and maintenance they are the most likely source of failure.

Much consideration must be given to these and other matters before the standard pressures for direct-current main-line working can be settled, especially as to whether there shall be two pressures or only one.

Electrical Machinery for Handling Goods and Minerals.

The limitations of an address do not admit of dealing adequately with the subject of railway electrical machinery for handling all sorts of general merchandise, goods and minerals. The subject is almost as essentially a railway problem as electric traction, but only a few general remarks are possible.

Perhaps it will surprise many electrical engineers to see from the table given for the use of electricity by 14 British railways that in 1918 these railways required 118,000,000 kw.-hours for lighting and power: 29 per cent of this was purchased and the annual one-hour load factor of this was 18 per cent. It will be appreciated how difficult it is to get the maximum one-hour demands correctly and this is probably too low. The annual one-hour load factor of the electricity generated by the railways for lighting and power was 32 per cent, varying from a minimum of 10 per cent to a maximum of 48 per cent, and for the whole use generated and bought 26 per cent.

It is interesting to note from the American return that their load factor for lighting and power is appreciably higher and of the order of 45 per cent.

The proportion of the total kilowatt-hours used in railway docks and in goods stations and yards may not be very great, but at the present time much attention is being paid to the mechanical handling of goods.

General merchandise is carried by railways at rates which may or may not include collection and delivery by the railway. A large proportion of the general merchandise is both collected and delivered, and the general internal trade of the country has during very many years been built up on this method, resulting in the handling of a vast number of packages of all sorts, shapes, sizes, and weights, each of which has to be checked in the goods station with its consignment note. This demands a special staff of men in a goods station for examining each article. Any method of handling goods mechanically will not dispense with these men and the faster goods are moved in the station the more men will be required to examine and check them, otherwise the speed of the handling machinery will depend on the speed of the checkers and callers off.

The whole railway methods of handling and hauling goods traffic have been built up gradually to suit the trader's requirements, and it must not be forgotten that, however much those requirements and the corresponding railway methods may be criticized, any complete system of mechanical handling must change the trader's methods of conducting his business, which is a far bigger matter than the design and installation of the mechanical appliances.

Under the present methods of working railway engineers have designed many schemes of conveyors and transporters which have been carefully considered, but few if any of them have been commercially acceptable.

In dealing therefore with general merchandise, where baskets of tomatoes or bags of potatoes may be followed by a ton of glass or a summer house, the mechanical appliances in goods stations consist generally of machinery for dealing with articles too heavy to be moved by hand. Fast travelling and traversing overhead electric cranes are ideal for this purpose since the goods platforms are left quite free. Without going into the reasons which usually require that in a goods station the roof stanchions which also support the crane gantry are spaced down the middle of a platform, it is becoming usual railway practice to attach a revolving jib to the bottom of the crab. This jib passes between the stanchions and is of such a length that the hook can command a siding or a cart road beyond the crane gantry on either side.

Until the entire habits of the traders are changed it does not seem possible to deal with general merchandise wholly by mechanical means, much as it would be to the advantage of the railways to do so. If it were possible the engineering problem with electrical machinery is quite straightforward. In a busy goods station in the west where two overhead cranes with underhung revolving jibs command the platforms, sidings and cart road and are generally in constant use day and night, careful checkings have shown that not more than 3 per cent of the total weight of general merchandise handled in any one day is moved by the cranes. Where existing buildings do not allow head room for overhead cranes or runways, electric jib cranes either fixed, or travelling on a mono-rail, are the only lifting appliances available, but they are a very poor substitute for the overhead travelling crane.

Travelling appliances transfer the goods from wagon to cart, or vice versa, and the overhead travelling crane comes to the wagon wherever it is and goes to the cart wherever it is, or vice versa. Power appliances are also required to move the wagons themselves, either full or empty, and include electric wagon lifts where station and yard are at different levels, wagon traversers to transfer wagons to or from any siding, turntables and capstans, and examples of such electrical machinery are to be found all over the country. A great deal of trouble has been taken to render the Clyde type of electric capstan suitable for railways. This capstan has a steel wire rope fixed to a free barrel, the barrel being clutched to the motor through the reduction gearing only when current is applied. As compared with the usual type of capstan with a barrel permanently connected to the gearing and a hemp rope slipping on the barrel the saving in the cost of ropes is reduced by from 80 to 90 per cent, and this saving generally more than pays for the electric energy, which is reduced by 50 per cent, as also is the electric power.

In a goods yard the goliath type of overhead travelling crane with a crab traversing along a bridge carried by a leg at or near each end and spanning one or more sidings and a cart road is the most useful loading and unloading appliance. The whole structure travels up and down the yard and with electric capstans usually completes the yard equipment, though one or more jib cranes at points inaccessible to the traveller may also be necessary. Some very fine examples of goliath electric cranes up to about 50 tons' capacity are to be found in our railway yards.

When instead of general merchandise of all sorts of shapes, sizes and weights special goods of nearly uniform size and weight have to be dealt with in large quantities such as bales of cotton, cases or boxes of food or merchandise; coal; ores or other minerals and grain of all sorts the whole can be loaded, transferred and unloaded mechanically and electric machinery is by far the most suitable where the work cannot be done by gravity. Doubtless a great deal remains to be done in the application of conveying or transporting machinery for such purposes, and this especially applies to docks and harbours, although several railway docks are well equipped with electrical machinery.

For dealing rapidly with large quantities of material of about the same size and weight, it is possible to design a conveyor to meet almost any requirement, supplemented with apparatus for loading on to the conveyor and for receiving the conveyed material. Excellent examples of conveyors for dealing with coal, ore, china-clay and other minerals have been provided by railways at their docks or harbours, but much remains to be done.

General Use of Electricity by Railways.

In addition to a large electric lighting load and a certain amount of heating and cooking, electricity is also used by railways for opening and closing Scherzer bridges, for working all classes of general machinery and in most departments of their locomotive, carriage and wagon works for driving machine tools, while the use of the electric vehicle from a 5-ton lorry to a platform trolley is increasing rapidly.

A word may be said about electric train lighting, which is one of the most difficult problems with which railway electrical engineers have to deal. The electric apparatus is an automatic central station, which ought to run for a month without attention. Essentially it consists of a battery, with a dynamo and with control gear to render the output of the battery continuous. By the use of the variable-speed dynamo in which the voltage is roughly constant, or under control between a lower limit and the maximum obtainable speed, the power taken from the locomotive driving each dynamo through a carriage axle may be reduced to reasonable dimensions. Railwaymen have been so intent on getting the whole plant reliable that not enough attention has been paid to economy in power. Experiments with different dynamos show for the variable-speed type at high speeds a saving over the non-variable speed type of some 40 per cent in the power taken from the locomotive for lighting.

Railway electrical engineering is a special branch of the profession demanding as much knowledge as can possibly be obtained of general railway conditions. An engineer requires all his youth for his engineering training and most of his manhood and middle age as well. He can usually only hope to pick up a smattering of general railway knowledge at second hand, and his success as a railway electrical engineer will largely depend upon his ability to absorb the knowledge and experience of his colleagues in other departments and

from the railway staff in general. Railway electrical engineering, apart from telegraphs and telephones, is almost wholly a development of this century and it has undoubtedly proved its usefulness. But it depends as much on the personal character as on the professional ability of railway electrical engineers and on their honesty in solving the many problems which are set them by the management, as to whether railway electrical engineering serves the railways, and through them the community at large, in the way in which it ought to serve both. I hope that this Institution will take a larger interest than it has done before in railway electrical engineers and that they in turn will in increasing numbers support this Institution.

NORTH-EASTERN CENTRE: CHAIRMAN'S ADDRESS

By W. Cross, Member.

(Address delivered 20 October, 1919.)

SOME NOTES ON THE INSTALLATION AND MAINTENANCE OF ELECTRICAL APPARATUS.

The efficient installation of electrical apparatus depends chiefly on attention to detail, and the aim of those carrying out such work should be to obtain :—

(1) Reliability ; for the resultant cost of a breakdown may be many times the cost of the faulty apparatus.
(2) Low first cost. This is especially required to-day, and should always be kept in view, as the more expensive material is by no means the most suitable in every case.
(3) Ease of maintenance and repair ; not only because this cost should be as small as possible, but because time is usually of great importance.

Many sets of rules have been drafted for installation work, the principal ones being the I.E.E. Wiring Rules and the Home Office Regulations for Factories and for Mines. Many of these rules are not clear and contradict one another ; in most cases they are not enforced and observed fully. For instance, in very few cases are rules calling for a switch to control a circuit of switch lampholders (I.E.E. Rule 110) or which state that a double-pole switch shall be provided for all apparatus over 600 watts (I.E.E. Rule 117) observed—people would object to the appearance of double-pole switches in their sitting rooms to control electric fires.

I think one set of rules should be drawn up stating certain broad principles, and that these rules should be enforced in all cases. These rules should call for the minimum requirements to ensure reasonable safety, instead of insisting on the use of the most expensive apparatus, as occurs in some instances at present.

Lay-out.—This is most important and should be arranged with a view to any likely extensions as well as to the immediate work in hand, as by this means expense may be saved in the future. Each individual job varies in some respect from every other, and only experience can enable one to decide the best material and arrangement in each case.

The number of fuses, switches, and other controls should be reduced to a minimum, as each joint or piece of apparatus is a possible source of breakdown. Almost invariably the distribution system of wiring is best (it is called for in most rules) and the cost is little, if any, more than that of other systems, while its flexibility enables additions and alterations to be easily made, testing is rendered simple, and current is cut off faulty sections only.

Although not clearly specified, and according to some rules even forbidden, I consider that all two-wire circuits (except on concentric systems) should be protected on both poles, even if one pole is connected to the middle wire of a direct-current three-wire system or to the neutral of a three-phase system ; as testing and disconnection are thereby facilitated.

The distribution boards should be fixed in accessible positions and it is worth taking trouble to see that controlling apparatus is arranged most conveniently for the user.

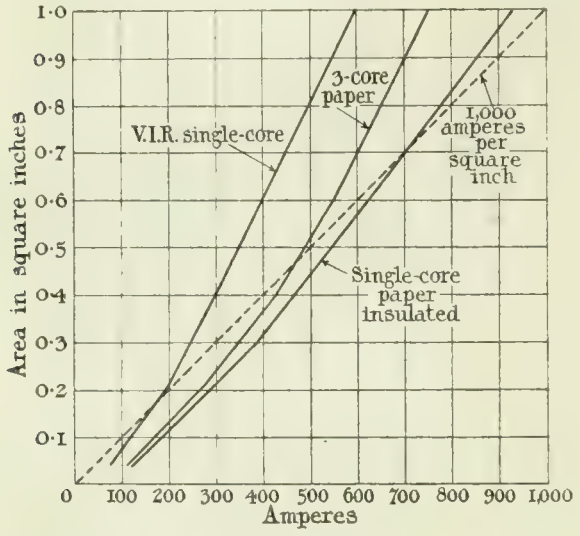
Regarding systems of lighting factories, warehouses and similar buildings, it will usually be found that general lighting rather than local lights will give the best results ; the current consumption will be little, if any, more, while the general illumination enables work to be carried out in any part of the room without altering the position of the lamps. The power required for lighting a particular area can be calculated by the following formula :

$$\text{Watts} = \frac{\text{area} \times \text{foot-candle intensity}}{\text{constant}}$$

The constant when using efficient reflectors will be 7 for half-watt lamps, or 4·5 with metallic filament lamps.

In engineering shops and similar buildings, if efficient reflectors are used, about 3 candle-feet gives a good illumination, and in offices about 4 candle-feet is required.

The number and size of the lamps will depend on the position of beams and other architectural features. In many cases it is most economical to use high candle-power half-watt lamps, but the size is often limited by the lowness of the building; for instance, with 100-watt half-watt lamps where 3 candle-feet is required, the minimum height of the lamp from the working plane is $7\frac{3}{4}$ ft., while with a 500-watt half-watt lamp the minimum height is 17 ft. This method must be used carefully, as each case requires individual treatment and common sense. For instance, I should not use many different sizes and types of lamps and



Curves showing current-carrying capacity of cables, based on temperature rise.

reflectors, as such an arrangement would be difficult for an average factory engineer to maintain properly, owing to the large stock of lamps of various sizes.

Cables.—Practically all cables used in this country consist of copper conductors insulated with vulcanized rubber, impregnated paper or, to a small extent, bitumen. Vulcanized rubber cable is finished off with braiding, or lead, or armouring, or lead sheath and armouring, or tough rubber. Paper cable is almost invariably lead covered (though during the war bitumen has been used instead of lead to some extent) and is then, if further mechanical protection is required, armoured with wire or steel tape. When deciding the type and size of cable to be used and the method of fixing the same, it is necessary to consider the conditions of each individual case and the cost of the job erected.

Quality.—I am unable to discover a satisfactory cable specification which will reject poor quality and pass cable of good lasting quality; and I find it necessary to trust almost entirely to the reputation of the makers. We have had more trouble with cable made to a stringent Government specification than with a much cheaper cable by an old established firm which we used on other jobs. I can recollect very few instances of true cable breakdowns, though a few years ago we had a number of faults due to faulty tinning of the copper conductors. In most cases the fault arises from mechanical or chemical external injury, often at or near the attachment of apparatus.

Size of cable.—The size of cable required depends, in the smaller sizes and on long runs, on the permissible drop in volts; and in the larger sizes and on the runs met with in most engineering works and shipbuilding yards, on the permissible rise in temperature.

To obtain the greatest economy, the size should be calculated by Kelvin's Law, which states that the cost of the energy lost in the line should equal the interest on the capital cost and the depreciation of the line; but the satisfactory working of apparatus, and the need of standardizing the apparatus (all for the same voltage) prevent this law being observed in most cases of internal wiring. I.E.E. Wiring Rule 40 specifies that the pressure drop for lighting circuits shall not exceed 2 per cent plus 1 volt, and that the size of cables for all circuits shall be such that the temperature rise shall not exceed 20 degrees F. for vulcanized rubber cables or 50 degrees F. for paper-insulated cables. It is necessary, however, with small motors or long runs to use larger cables than those allowed if temperature rise only is considered, as otherwise the pressure at the motor or other apparatus will be too low for efficient operation.

I have plotted curves showing the relation of sectional area to maximum current carried at not more than permissible temperature rise, the figures being taken from the I.E.E. Rules and other well-known tables. It will be noticed from this diagram that paper-insulated cable can safely carry more current than vulcanized rubber cable of the same size. The current density with vulcanized rubber cables varies from 4,000 amperes per square inch with 1/18 S.W.G. to 595 amperes per square inch with a 1-inch cable, the 1,000 amperes per square inch current density being found with 0·15 sq. in. cable. With three-core paper-insulated lead-covered cables, the densities vary from 4,000 amperes per square inch for 0·07 sq. in. (7/20 S.W.G.) to 745 amperes for a 1 sq. in. cable, the 1,000-ampere current density being for about 0·46 sq. in. area. With single-core lead-covered cables the current density varies from 4,000 amperes per square inch for 1/18 S.W.G. to 932 amperes for 1 square inch, the 1,000-ampere current density being found at about 0·68 square inch.

Owing to the reduced carrying capacity of large cables, it is sometimes cheaper to use two or more cables instead of one, but each case must be considered on its merits.

Cable protection.—The following are some of the more usual methods of supporting and protecting vulcanized rubber cables:—

(*a*) On porcelain insulators, with tubing where subject to mechanical injury. This is, I consider, the most satisfactory method (apart from its low cost) in engineering shops and other premises, but tubing should

be used where mechanical damage is likely, so as to prevent unsightliness and risk of shock. This system is certainly the safest and most satisfactory in wet or hot situations or where chemical fumes are present, but it is desirable in these cases to clean the insulators and examine the wires periodically. I do not consider this system to be suitable for houses, shops, offices or similarly constructed buildings.

(*b*) Metal-covered systems have been developed by various firms, but I have not found them thoroughly satisfactory on 240-volt d.c. circuits, probably through bad earthing of the covering. I think the methods of bonding might be improved and that a conduit box with cone nipple and lead wool for bonding the metal covering to the box would be satisfactory.

(*c*) Wood casing was very much used in earlier days and makes a sound job when dry and free from chemicals, but it requires more labour for erection than other systems. I have known faults due to the wood fillet being impregnated with chemicals and moisture from the walls of buildings which also destroyed the insulation, setting up an arc from cable to cable. In one case of this nature I was able to investigate the matter fully and I found that a 1-ampere arc was passing over the fillet, making the wood red hot but not causing a fire, though I believe a fire would soon have developed. I suggest that with wood casing it is safer to have cables of different polarity in the same groove as a fault then will blow the fuse more quickly.

(*d*) Close joint tubing has been used here more than any other system for houses, shops and offices, and though in many cases no attempt has been made to make the lengths of tubing continuous or to earth it, very few faults have occurred. A grip system is called for by the I.E.E. Rules, but the efficiency of this depends largely on careful workmanship.

(*e*) Screwed tubing in cases where insulators are unsuitable is, I think, the best system to use, though the cost is great. It should always be erected with draw-in boxes before the cables are drawn in, and as far as possible should be kept away from positions where change of temperature occurs, as this causes condensation and breakdown of the cables. In one case frequent breakdowns occurred where the cables passed up from a hot subway to a room at ordinary temperature, and in another case the cables failed each autumn in a heating subway which was hot in winter and cool in summer when the fires were not in use.

Paper cables, either lead covered or lead covered and armoured, are usually fixed without further protection; all ends must be properly sealed in boxes. They are not suitable for temporary work or short runs, as the cost of boxes and fixing the same is in those cases excessive.

Leading in cables.—The method of leading cables into apparatus and connecting up deserves much more attention than is usual, as faulty methods—

(1) Prevent a satisfactory job and are a great cause of breakdown.
(2) The work involved in fixing and repairing or disconnecting takes longer than is necessary when time is most important.
(3) The cost of testing, dismantling and repairs is greater than necessary.

For instance, when one finds that to connect up an oil switch it is necessary to spend 4 or 5 hours in taking the switch to pieces or in sweating in a vertical position, one feels that the designer does not know his business and should have the punishment of fixing the apparatus.

I suggest—

(1) That all cable sockets should be so arranged that they can be sweated to the cable away from the apparatus and then bolted to the apparatus.
(2) That earthing sockets should be provided on all apparatus by the maker who can fix these far more cheaply than the men who erect the apparatus, probably without any facilities for drilling, etc.
(3) That inlet holes of ironclad gear should be drilled by the makers for a suitable pipe to take the correct size and number of cables, and provided with a wood bush at each hole so that cable can be run in unprotected or in tubing as desired.
(4) That in the case of distribution boards an iron plate easily removable should form one side. This iron plate would then be unscrewed and drilled as required, a much simpler job than drilling the case which is inclined to crack. The latter arrangement is a very great convenience to the erector.

The arrangements of leading in cables, connecting up and fault finding for motors are usually badly designed, and it is impossible to connect them up neatly and efficiently. I consider that a terminal plate should be provided to which all connections of field coils and armatures, rotors and stators should be brought. If these terminals are equally spaced, it is possible to make the necessary rotor connections with brass strips of one size: all terminals should also be marked in a standard method. The advantages of this arrangement are very great, as any portion of the motor can be easily tested and alterations to the connections made without trouble.

This terminal plate should be fixed on the side of the motor and covered by a square iron box with an entering hole for the cable on one side, held by four studs spaced equally so that the box can be turned so as to bring the hole by which cables enter either at the top, bottom, right-hand side or left-hand side of the terminal box.

The cover of the box would be removable to connect up the motor, etc. With this arrangement, the wiring can be run with ease into the motor and fully protected all over. If slide rails are used, flexible tube will be suitable protection, and a dividing box can be attached to the box if paper cable is used.

Earthing.—In factories earthing is most important and should receive more attention than is usually the case. All metal (other than trolley wires and similar apparatus placed out of reach and clearly carrying

current) that can be accidentally touched should be earthed, including the cases of arc lamps and meters.

Bolts and nuts are not efficient, their resistance being great. In one case which came to my notice, a cable junction box in which nuts were used for continuity burnt through when a dead earth occurred.

The current that may pass when an earth occurs may be very great, causing a high pressure near the fault if the resistance of the earth connection is great.

In practice I find that if one uses a 7/20 S.W.G. (0·007 sq. in.) cable for each 60 amperes normal current taken by apparatus, with 7/20 S.W.G. as a minimum and an equivalently larger area for greater currents, the results will be satisfactory. Screwed tubing and piping can, for lighting and small power circuits, be safely used instead of an earth wire, but the joints should be few.

Maintenance and periodical testing of all earth connections is most important, as the lack of an earth connection does not usually show itself in the working of apparatus. All connections should be traced out as far as possible to see their condition, and a rough test with a bell and two cells will show the continuity reasonably well.

In factories and in such places in private houses where a person may be in contact with earth (e.g. in a bathroom) the switch cases and knobs should be earthed or insulated; many tumbler switches with porcelain covers have metal knobs, this being as unsafe as unearthed switches with metal covers.

Rating.—The rating of apparatus should receive more attention than has been the case in the past; few switches will properly break the current at which they are rated 100 times, and I do not think they would be capable of passing the I.E.E. test, which states that they must break a circuit with the pressure and current 50 per cent in excess of their rating; and the average fuse will not clear a light-duty short-circuit. I suggest that samples of accessories should be tested and that the rating should be calculated from these tests; it would be necessary for the British Engineering Standards Association, or other authority, to specify a standard test which might be made by the suggested National Proving House. Such test should not be too stringent, as we must endeavour to cheapen the cost of electrical work; and it should be made under working conditions as far as possible.

Standardization.—It is also very desirable that material should be standardized not only because the cost of production will be reduced, but that one of the principal troubles of maintenance work will be eliminated. It is very costly and irritating to find, when carrying out a repair miles away from any supplies, that the dimensions of apparatus vary from the standard.

Sockets, in particular, should be interchangeable as regards centres and diameters of pins; there are many types fixed which cannot now be obtained, so new types have to be supplied if extensions are wanted or a plug is broken or lost. We met this trouble many years ago and adopted a well-known, though at that time expensive, make, and can now supply plugs from stock to fit sockets fixed 15 years ago, so the adoption of a standard has well repaid us. Although rules call for sockets interlocked with switches, very few are marketed, and there is a good field for these, particularly to carry safely 10 and 20 amperes for heaters in private houses, for which purpose they must be neat and unobtrusive.

Maintenance.—This is often neglected, and it is surprising that more accidents do not occur. Often in going over an existing installation I find the work in very bad condition, and additions badly executed, breaking the most important rules. Insulation resistance does not show that the installation is in good condition, for with dry wood casing the wires could be absolutely bare and yet give a good test, but it is useful to find out certain faults. I think that every job should be overhauled periodically by a competent man.

Labour is one of the most important factors in an efficient installation. Unless the workmen actually carrying out the work are efficient, the job will be unsatisfactory, even with the best material; in fact I think I would rather have poor material and good labour than good material and poor labour.

In conclusion, it will be seen that the most important factors in an efficient electrical installation are:—

(1) A properly designed scheme drawn up by an engineer who knows what material is most suitable for the conditions of the particular job.
(2) Suitable apparatus properly designed and manufactured so that it will easily fit the other parts of the installation and can easily be maintained and repaired.
(3) Efficient workmen who can be trusted to fix and connect up apparatus properly.
(4) Proper maintenance to prevent faults developing, so as to cause danger or serious breakdown.
(5) Standard specification and rating of apparatus and accessories.

If all work is carried out on these lines, I am confident that there will be brighter and more prosperous times for all in the electrical industry.

IRISH CENTRE (DUBLIN): CHAIRMAN'S ADDRESS

By RICHARD TANHAM, Member.

(Address delivered at DUBLIN, 16 *October*, 1919.)

(ABSTRACT.)

Our retiring President (Mr. C. H. Wordingham, C.B.E.) in his address to the Irish Centre (Dublin)* delivered here in May last, referred briefly to the part that should be played by the Institution in the period of industrial revival now at hand. I should like to avail myself of this opportunity of strongly recommending junior electrical engineers and pupils in this Centre to join the Institution. All electrical engineers possessing the necessary qualifications should be identified with it; and each of us should use his best endeavour to introduce eligible friends to the meetings and secure their admission to the Institution. I also take this opportunity of drawing attention to the Informal Meetings that have been held in London for the purpose of helping and encouraging the younger members, and I think it would be an excellent arrangement to hold one or two such meetings each session at this Centre for the same purpose. I feel sure that all the experienced members would be glad to lend a helping hand; and in this manner our younger members would be afforded an opportunity of getting practice in the reading and discussing of papers. I know how most of the younger men view this matter, and some of them have already expressed the wish for such an opportunity. Encouragement in this direction would, I feel certain, bring out new and interesting subjects and create a keener interest amongst the members.

The Institution is of increasing value both to the members and to the country; we all may be able to perform our duties individually, but our usefulness no one will deny is greatly increased by acting in co-operation. This Centre has often criticized the shortcomings of the Institution, and I am sure we all note with pleasure that many of the progressive measures suggested by Mr. Wordingham have already been inaugurated, and in time, no doubt, his whole programme will be successfully developed; at any rate it can no longer be said that the Institution is not taking an active part in the material welfare of its members and of each section of the electrical industry.

From a perusal of the opening addresses delivered by members of this Centre, not to mention the many valuable contributions, it is evident that it is becoming increasingly difficult for the Chairman, following so many distinguished past chairmen, to choose any particular subject of local interest for his address. I feel this handicap very much because practically all the schemes which seem of interest and importance at the present time have received attention. Members have, for instance, shown on various occasions the value and the necessity of developing our peat and water resources. The former may ultimately be the solution of power distribution in Ireland; the latter, where within reasonable distance from the place of demand and where the whole of the power can be absorbed during the day and night, should be immediately developed, linked up electrically and connected to existing steam stations. We should also look into the question of adopting suitable apparatus and methods for using different kinds of coals not hitherto regarded as suitable or commercially available. The three natural sources of power in Ireland, namely, peat, water and coal, have recently been the subject of investigation by three separate Government Committees, and their reports are awaited with the greatest interest.

The subject of fuel economy would not have attracted any very special attention to-day were it not that the country is compelled to consider it and for several assigned reasons—among which may be mentioned conservation, enhanced price, scarcity of supplies, and development of industry. This country is at the mercy of every strike or industrial disorganization and it is not possible to build up sufficient reserve stocks. Great Britain may have to reduce our fuel requirements at any time, and from almost every point of view it would appear that facilities should be granted for the rapid development of our power resources. In these days every country is, or should be, making its best endeavour towards maximum production and conservation of resources; now is the time to develop ours and create a position less dependent on the imported article.

Ireland, in common with all other countries, has had to fall in with the fuel economy policy of to-day. Every power station and consumer of coal has had to adopt means of more efficiently utilizing supplies. Effective restraints were put into force against unlimited use of fuel; consumers were obliged in many cases to remove or repair inefficient apparatus and replace uneconomical methods of operation. Electric power stations and factories were compelled to adopt methods towards the conservation of high-grade coal by the use of low-grade coal.

To correct the extravagant use of coal the first and most obvious method was adopted. Engineers were appointed to assist the Government in a fuel-economy campaign; in this way considerable savings were effected in the amount consumed by eliminating losses

* *Journal I.E.E.*, 1919, vol. 57, p. 421.

due to careless and inefficient operation. Most of the members are no doubt acquainted with the methods of procedure and I do not propose to go into details, but as the matter is one of burning interest to electrical engineers, and as there is nothing more important at the present time than fuel economy, I should like to refer briefly to the results obtained in electric power stations.

The progress that has been made and the increased efficiency obtained with the growth of the power-station industry is remarkable, and we all know that the power-station industry has now become a necessity to the economic life of the nation.

We have in Ireland 13 power stations using coal and furnishing technical returns to the Board of Trade Coal Mines Department. During the year ending 31st March, 1918, the total number of units generated by these stations amounted to 59,159,700. The total consumption of coal in the 13 stations amounted to 117,640 tons. The following year ending 31st March, 1919, the number of units generated was reduced by 3,119,365 and a saving of 5,667 tons of coal was effected.

Power station engineers during the past year adopted every possible means towards the efficient control of the apparatus at their disposal, which in many cases is not of the most modern type, and everything possible was done to obey the fuel-saving edict of our late Coal Controller. In my opinion the result, having regard to the load, the available plant and the quantity of low-grade fuel consumed, may be considered satisfactory. Needless to say, all the methods so far adopted only touch the fringe of fuel economy as it is understood to-day.

Electric power stations in Great Britain and Ireland using coal- or coke-fired boilers have been divided into areas and groups. Area No. 22 denotes Ireland, and the figures obtained last year give her 12th place on the list of areas arranged in the order of lowest average for pounds of fuel consumed per unit generated, and 17th place on the list of areas arranged in the order of highest thermal efficiency. The average consumption of fuel per unit generated in Ireland last year was 4·50 lb. and in the United Kingdom 3·459 lb.

The average calorific value of the coal delivered at my station during the year ending 31st March, 1918, was 11,050 therms per lb., and last year the average fell to 9,840 therms per lb. The thermal efficiency of this station during the first-mentioned year was 9·02 per cent, and last year 8·90 per cent. The coal consumption per unit generated increased from 3·41 lb. in the year 1918 to 3·90 in the year ending 31st March, 1919.

Members will note from the above figures that the number of therms used per watt-hour generated was 37·68 and 38·37 respectively for the two years under review. These figures may be taken as the best that can be obtained in Ireland under prevailing conditions in stations using coal-fired boilers.

In the year 1894 a figure of 117 therms per watt-hour was given as an average for 23 English power stations, and 32·6 therms per watt-hour generated was considered a possible figure for ideal works; now 27 therms per watt-hour generated is considered to be common practice, and in power stations with good load factors and modern plant 20 therms per watt-hour generated has been obtained.

The highest thermal efficiency of any power station in Great Britain and Ireland generating between 3 and 15 million units per annum during the year ending 31st March, 1919, was 11·19 per cent, and the lowest fuel consumption per unit generated was 2·61 lb. There are 114 power stations in this group and four of them are situated in Ireland. For power stations generating between 15 and 50 million units per annum—and in this group there are 53 stations—the lowest fuel consumption per unit was 2·19 lb. and the highest thermal efficiency 14·05 per cent. Altogether there are 438 power stations included in the completed summary of the Coal Mines Department. Eighteen of these are stations generating over 50 million units per annum and the total number of units generated last year by these 18 stations was 2,038,492,583, while the total for the whole 438 stations was only a little more than double this figure. The highest thermal efficiency obtained last year at any station in Great Britain was 18 per cent, and the lowest fuel consumption per unit generated was 1·80 lb.

It has been estimated that the average coal consumption per unit in the year 1888 was 24 lb. Now we know that it is possible to obtain a coal consumption of less than 2 lb. per unit, using coal having a thermal value of 11,000 therms per lb. Members will have noted the remarkable results concerning the working of the Connors Creek power station where a kilowatt-hour is generated for a consumption of 1·42 lb. of coal, and electrical engineers hope to keep on improving the efficiency so as to reach the ideal now desired, viz. one kilowatt-hour delivered on the switchboard for each pound of coal consumed.

Our past Chairman, the late Mr. J. P. Tierney, in his address * referring to the electrification of railways gave a figure of 6 lb. of coal per horse-power-hour for steam locomotives, and it is interesting to compare this figure with the one now obtained in power stations. If we take figures for power stations and distribution efficiencies now admitted to be within the range of established working conditions, we have 1·80 lb. of coal per unit; allowing about 10 per cent for falling off of plant efficiency and varying conditions of operation we arrive at a figure of 2 lb. of coal per kilowatt-hour. The efficiency for conversion and line losses representing American railway practice are as follows:—Step-up transformers 98·5 per cent, step-down transformers 97·5 per cent, conversion plant 88 per cent, trolley line 90 per cent, electric locomotive 88 per cent. The combined efficiency from the switchboard to the drawbars of the electric locomotive works out at 63·4 per cent. We thus arrive at a figure of 2·35 lb. of coal per horse-power-hour at the locomotive. It would appear from this simple consideration that coal conservation by electrification of railways is likely to be carried through at a rapid rate in the near future, particularly on suburban lines and where a large amount of shunting work has to be done, and it is important to note that most of the fuel saved would be high-grade coal. There is

* *Journal I.E.E.*, 1919, vol. 57, p. 27.

more than one railway in our own country where an immediate saving of coal could be made, and I believe a profitable result would follow electrification of a portion of our local lines. Main-line electrification will also offer considerable opportunity for coal conservation, and in this connection we may expect to hear of several interesting propositions besides electrification by means of the stationary power house and transmission line.

The thermal efficiency referred to above is the ratio of the total electrical energy delivered at the switchboard to the total energy in the fuel as fired, and takes into account all losses. This figure to the electrical engineer is a very important measure of progress. We have seen that 18 per cent was the highest attained last year in Great Britain and 8·9 per cent in Ireland. In America during the year 1913 a large unit of 20,000 kw. capacity with turbo-generator, boilers and auxiliaries attained a thermal efficiency of 18 per cent, and in the year 1918 a 35,000-kw. unit reached a thermal efficiency of 21·6 per cent (this latter figure has probably been improved during the current year). The steam turbo-generator unit has not yet reached its maximum efficiency and it is calculated that in the near future 26 per cent will easily be realized.

The economies offered by large power stations reflect the greatest credit on all concerned, and when we compare the above figure with the small stations generating electricity and consuming from 10 to 20 lb. of coal per unit, as must be the case in such stations as the Lucan Electric Railway, the Great Northern Railway Company's power station at Sutton, and the Dublin Port and Docks Board station, and other industrial and private plants, it is not surprising that the tendency is towards the compulsory closing down of such stations where it is known that a considerable amount of the nation's greatest birthright is being wasted every day.

To the steam turbine with its increasing size and efficiency must be attributed most of our power-station progress. The first large steam turbine of the vertical type was installed in Chicago in 1903 and was guaranteed to give a thermo-dynamic efficiency of 50 per cent. In recent years 35,000-kw. turbines have been installed and the thermo-dynamic efficiency is now about 80 per cent. I had the opportunity recently of seeing a couple of sets approaching the latter size, one a B.T.H. turbo-alternator of 30,000-kw. capacity for the Rotherham Corporation, the other a British Westinghouse turbo-alternator for Clyde Valley. The maximum continuous output of the B.T.H. alternator at 0·75 power factor is 40,000 k.v.a., voltage 6,600, amperes per phase 3,490, and the speed 1,500 r.p.m. The turbine is designed to work on a steam pressure of 220 lb. per square inch and 200 degrees F. superheat. The most economical load of the set is 25,000 kw. and the thermo-dynamic efficiency 76·3 per cent. The highest thermo-dynamic efficiency reached in America during the year 1917 is stated to be 78·7 per cent.

Since the year 1905 the development of the turbo-generator has been very rapid, and it is interesting to follow the growth of the sets since that year. In 1905 d.c. engine sets of 3,000 kw. capacity, and a.c. engine sets of 5,000 kw. capacity were the maximum sizes in that year.

Water-driven turbo-alternators increased from 12,000 kw. capacity in 1905 to 32,000 k.v.a. in 1919.

Steam turbo-generators of 3,000 r.p.m. were of about 1,000 kw. capacity in 1905, 3,500 kw. capacity in 1910, and 10,000 kw. capacity in 1915.

Steam turbo-generators of other speeds reached 12,000 kw. capacity in 1905 and more than doubled their size in the following five years, reaching 27,500 kw. capacity in 1910, 36,000 kw. capacity in 1915, 45,000 kw. capacity in 1918, and 60,000 kw. capacity in 1919. It is frequently stated that the increase in the size of the turbo-generator or the individual output per set is closely associated with cheap power, as the capital charges per kilowatt are reduced and the efficiency is increased.

This rate of development reflects the greatest credit on electrical and mechanical engineers and is a record of progress that cannot be excelled in any other branch of engineering. This is not the end, for we are promised increased efficiency by the use of higher steam pressures and temperatures and by "bleeding" or tapping the turbine at two or more places, placing heaters in series, pumping the condensate through them in contra flow and direct from the condensers to the boilers. The economizer might be retained as a form of air heater, the air being heated by the gases and delivered to the boiler for combustion purposes. In the Connors Creek power station members will have noted that the heated air coming from the electric generators, steam pipes, etc., is lead to the boiler furnace, because for each kilowatt generated about 100 therms can be recovered. Another notable progressive proposal is Mr. Emmett's two-fluid method, using in this case mercury and steam. He superimposes on the steam temperature a high temperature by the use of mercury vapour. The expected efficiency is very great, meaning some 40 per cent saving in fuel; but progress has been delayed by pressure of war work.

Whilst it is recognized that the steam turbine has revolutionized power-station development and that greater freedom in the choice of station sites with a plentiful supply of water has been greatly faciliated by high-tension transmission; boiler-house improvements have also made great advances.

Automatic stokers, steam-raising devices, recorders and auxiliaries have contributed considerably towards improving thermal efficiency. As the size of the turbo-generator increased so also did the size of the watertube boiler expand. Boilers are now installed in Great Britain for an evaporation of 70,000 to 80,000 lb. per hour, and some are capable of an overload duty of 104,000 lb. of water per hour from and at 212° F. In America, at Detroit, a peak load duty of 100,000 lb. per hour per boiler is carried and up to 160,000 lb. per hour is expected. Boiler working pressures are also on the increase, at Glasgow 275 lb. per square inch is to be used at the new Dalmarnock station. At Carville power station 275 lb. per square inch, and for the new Barton station at Manchester a boiler pressure of 375 lb. per square inch is contemplated. At Detroit station plant is working at 350 lb. per square inch and at the

British Thomson-Houston Company's power house at Rugby there is a 350 lb. per square inch pressure plant with Babcock and Wilcox self-contained marine-type boiler, that is, boiler, superheater, economizer and stoker inside one casing. This plant was designed by Mr. Samuelson and put into service in the year 1914. I saw it after almost four years' continuous working and everything appeared to be satisfactory. The turbine has been opened up for inspection and the blading found to be in first-class condition. There are 217 self-contained boiler units actually in operation and the capacity of these boiler units varies from 25,000 to 90,000 lb. evaporation per hour. I briefly refer to the above installations to draw attention to the efforts that engineers are making towards conservation of resources and providing power at a cheaper rate. I am preparing a high-pressure boiler and turbo unit scheme to compare with the running of present plant at my station and with a view towards increased economy in connection with future extensions.

The use of low-grade fuel is now a matter of considerable importance and is worthy of close investigation in this country particularly. Investigation into production and methods of utilizing low-grade fuels and developments in other countries have demonstrated that the use of such fuels may be made to afford economies.

Stoker apparatus for forced draught has been on the market for a number of years burning low-grade fuel; there are 32 forced-draught travelling-grate stokers at the Gas de Lyon burning coke breeze, and at the Priestman Colliery Company's Whinfield power station there are four small Stirling watertube boilers equipped for burning coke breeze. Two large Stirling boilers, each having a capacity of 35,000 lb. of steam per hour when burning coke breeze, are equipped each with two forced-draught travelling-grate stokers. Altogether some 725 of these stokers have been manufactured in England, and counting those made in France, Austria and Germany the total number manufactured would be 1,500. I should here like to mention that to burn coke breeze and to burn Irish anthracite is not quite the same proposition, although the average percentage of volatiles in each is about the same; there is a considerable difference in the physical properties of coke breeze and anthracite.

Several tests and experiments have been made with existing stokers as at present installed, but it has not been found possible, so far as I am aware, to burn Irish anthracite coal in sufficient quantity or at a sufficient rate to meet large power-station conditions. I have had experiments made but could not burn this fuel on the apparatus at hand except on one boiler, and with this only obtained an evaporation of 4·9 lb. of water per lb. of coal from and at 212° F. with a consumption of 14·6 lb. of coal per square foot of grate per hour; we want to be able to burn at least 25 lb. of coal per square foot of grate per hour. The makers of the forced-draught travelling grate stokers claim that their stokers will burn Irish anthracite coal at this rate, and I understand a number of these stokers are at present being installed at the Corporation electricity works.

Forced-draught travelling-grate stokers installed at the Lambton and Hetton Colliery, Philadelphia, power station where a great variety of fuel has been burned varying from rough small of high calorific value to colliery waste have, I am informed, burned anthracite coal with excellent results. At an anthracite colliery in the Swansea district there is a forced-draught stoker on a Babcock and Wilcox boiler of 6,182 square feet heating surface and I understand its ability to burn anthracite successfully was fully demonstrated.

Amongst the many other devices suggested for more efficiently utilizing our fuel resources may be mentioned one recently installed at the Hammersmith electricity works. I refer to powdered fuel; this process is by no means new, it has been in use about 25 years in America principally in the cement industry, and incidentally I might mention that this fact is worth bearing in mind in connection with the development of cement manufacture in Ireland. Patents for a process of burning powdered fuel were taken out in England 80 years ago and for a means of firing a locomotive boiler in America a patent was granted in 1881. During the last decade there have been many powdered fuel plants put down, but it is only recently that developments have been able to overcome difficulties experienced with powdered fuel for use in stationary boiler plants. Installations are now being put down in power stations and the results will be watched with the greatest interest.

In America the consumption of coal in powdered form is about 10 million tons per annum, the consumption being approximately as follows:—

Manufacture of cement	6,000,000 tons.
Iron and steel industry	2,000,000 ,,
Production of copper	1,500,000 ,,
Generation of power	200,000 ,,

In addition the development of fuel in this form on board ship and on locomotives is now under way. A trial locomotive has been designed at the Gorton works of the Great Central Railway and there are railways in Brazil and Sweden operating with such fuel; in the latter country powdered peat is used successfully for this purpose.

Powdered-fuel supply companies are now formed in America and deliver fuel in containers for use in apartment houses, office buildings, and hotels. One company ships and delivers the powdered fuel in special tank wagons and from these it runs into the customers' receptacles. The trouble at present appears to be connected with the furnishing of the apparatus which is holding up development.

During recent years American engineers have been practically forced to find a suitable fuel to help out the falling supplies of natural gas. This has led to the close investigation of powdered fuel, and so far as bituminous coal is concerned the results show that the use of pulverized coal has now passed the experimental stage. Recent advances with this method of burning fuel have shown marked economy and it will likely be more widely used when it is better understood. The question of greatest interest to Irish engineers is: will this method of burning fuel be applicable to Irish coal or peat? It is claimed that by pulverizing fuel and applying it in the correct powdered form,

both high-grade anthracite, bituminous coal and coal of lower commercial value, also peat, lignite, colliery waste heaps, waste anthracite culm are now being successfully burned.

There is a very interesting report issued by the Fuel Research Board on pulverized coal systems in America. This report consists of notes made by Mr. Harvey who investigated the matter last year in America on behalf of the British Government. I have been in correspondence with Mr. Harvey and he informs me that he has followed the coal situation in Ireland very closely and has been in touch with Mr. Burgess with a view to giving evidence before the Irish Coal Commission on the subject of using Irish fuels, especially anthracite culm and Irish peat. He also informs me that Irish anthracite containing 5 per cent volatile and 4 per cent ash would be an exceptional coal to be used in pulverized form. The content of volatile matter would be quite sufficient to maintain continuous firing in power-station boilers, and the plant could be run for very long periods without cleaning. Semi-anthracite coal would also be ideal fuel, containing 15 per cent volatile and 20 per cent ash.

There are numerous details in connection with the design of burners, furnaces, drying and powdering the fuel, and there are many practical points of importance when burning low-grade anthracite that differ from those used when burning bituminous coal, such as reversal of the flame, a method not resorted to when burning bituminous coal.

I venture to state that the powdered fuel system is worthy of careful investigation in this country and should receive financial aid from the Local Advisory Committee of Scientific and Industrial Research on the lines already granted for industrial research.

WESTERN CENTRE: CHAIRMAN'S ADDRESS

By Arthur Ellis, Member.

(*Address delivered at* Cardiff, 3 *November*, 1919.)

(ABSTRACT.)

Electricity Supply Bill.

Under this Bill there will be set up a Board of Commissioners who will have absolute control, subject to the Board of Trade, of the whole of the electricity supply industry throughout the country. They will be empowered to devise some comprehensive scheme of supply and distribution in bulk, and adopt methods suitable to the conditions prevailing in the different areas. The powers conferred by the Bill upon the Commissioners, if carried into effect in the right spirit, will be of undoubted advantage to the whole community.

The formation of District Boards will be suspended for the time being, in order to give those interested a fair opportunity of devising schemes suitable for such areas, failing which, District Boards will be set up to take over sole control.

This was one of the objectionable features of the Bill when originally presented, and which fortunately has been removed, as I think it was generally felt that in some cases District Boards would be set up which would be comprised of individuals having no knowledge whatsoever of the electrical industry or of the requirements of any particular area. If those already interested and controlling the industry in any particular area fail, however, to devise a scheme which will satisfactorily deal with the situation, of course they themselves must accept the responsibility and the one and only alternative.

I am one of those who would favour the formation of a District Board at the outset, comprising the technical representatives of the various undertakings in an area; and if, and so long as, they enter into the business with an entirely open mind, without any prejudice regarding their particular undertaking or any other, I feel satisfied that only good work would ensue, and that a Board constituted in this way would be of undoubted advantage to the Central Board of Commissioners in London.

I would at no time include the direct municipal representatives, as they, to an extent, must be influenced by local sentiment. The local technical representatives ought to be able to devise a scheme or arrangement of interests such as they would draw up if they were either financially interested or affected by the results obtained.

This is not an opinion resulting from any intended severance with municipal work, but one which I have all along held. In fact, during negotiations which have extended over a period of years with an important local company, I went so far as to suggest to the company that if they were able to put up a power station and generate and sell at a lower cost than that at which we are able to do from the local authority's station, I would be prepared to advise such authority to take a supply in bulk, and this is, I think, the proper view for anybody to hold.

A particularly good feature in the Bill is that relating to wayleaves, which will most certainly affect most undertakings, and particularly that with which I have been connected during the past 19½ years, but which I am about to leave, in order to join that branch of the

profession which our immediate Past Chairman in his Address last year * considered to be a fast disappearing one. However, I hold somewhat different views to-day.

Another good feature of the Bill is that relating to existing areas, which in the past have suffered as a result of being too restricted in regard to not only lighting and power supplies, but also—and what is of equal importance—transport facilities. A particular district must not be denied a supply simply because the authorized source of supply for the district is remote, whilst some other source may be available at the boundary.

Considerable thought will have to be given to the effect that will ensue as a result of scrapping machinery and plant already existing, the cost of which will have to be taken into account in connection with new stations that may be erected, controlling, as it will do, the prices chargeable to consumers.

The proposed super-power stations are not going to be set up in a day or two. In fact, it may take years to get everything properly arranged, and yet something must be done in the meantime to supply the increased demands, and it occurs to me that perhaps some form of linking-up of groups of stations, not far remote one from the other, would be easily arranged pending the development of the larger scheme. In this connection there is another matter which, in my opinion, is of considerable importance, viz. the attitude of the individual who would desire to take a public supply and meantime has to install his own plant. Such plants may not comply with standard requirements and so make the work of connecting up to the public supplies somewhat difficult—in many cases necessitating the scrapping of the plant.

During the period of the war, everybody requiring plant and machinery, no matter for what purpose, had to obtain a permit from the Ministry of Munitions, giving their reasons for wanting such plant, together with its type and other details. If the Board of Commissioners could continue this principle of control during the development of the larger scheme, they would be able to ensure that all private installations would be capable of being coupled up later to the general supply without any substantial alterations being necessary.

The question of frequencies, voltages, and systems of supply in different areas ought to be settled without delay, so that prospective consumers will know what to provide for. In fact, it might be found in certain areas that the whole difficulty could be solved in this way, especially in those areas where no appreciable amount of waste-heat gases is available.

Then, again, present-day prices of plant, affecting the cost of super-power stations, is a very serious matter and, rightly or wrongly, I see a danger in having the whole of the electrical supplies controlled from a too limited number of super-power stations.

The possible attitude of labour in the future must also be taken into account. The fact that the Electricity Supply Bill will make it a penal offence for employees of electricity supply undertakings to cause interruptions to the supply by striking, under certain conditions would not have much weight with some of the more extreme leaders of labour, and we want to avoid increasing the number of weapons already used for enforcing unreasonable demands upon the community, bearing in mind the influence such leaders have with large bodies of workpeople generally.

Also, we must not overlook the disadvantages resulting from the setting up of super-power stations, such as interruptions of supply to large areas through breakdowns of large units or in the overhead transmission lines, as against existing ones which are only local in effort.

It will undoubtedly be a case of smaller stations, and even those of medium size, automatically disappearing and being absorbed by the larger.

There is another feature in connection with the Bill which requires some clearer definition, viz. the clauses relating to charges for bulk supplies, which present certain difficulties, notwithstanding the fact that it is laid down that those whose stations may be taken over shall not pay higher rates than those at which they were able to generate power themselves.

Due allowance ought to be made in the case of stations the owners of which have been waiting for the termination of the war in order to carry into effect alterations and extensions of plant, also the scrapping of plant which has become obsolete, in order further to reduce their cost of production, all of which might be done without any appreciable expenditure of capital. I hope that such facilities will be readily afforded in the meantime and full advantage taken of them. Further, it is hoped that under such an arrangement one district will not be made to subsidize another and consequent hardships be imposed.

However, I think we are all agreed that the Bill, subject to certain amendments which are likely to be made, will be welcomed as a means of effecting the economical production and distribution of supplies, which, in turn, will affect the production of all other industries and help the country generally to avoid slipping back into conditions that might reasonably be termed hateful, involving, possibly, national bankruptcy.

Before leaving this subject, there is a matter to which I should like to make reference, regarding the Reports upon which the Bill has been very largely based. I am afraid I must come into conflict with our Past Chairman regarding the development of the electrical industry by municipal authorities, which, in his opinion, has been disastrous, whereas I consider that the credit which is due to them has not been given.

I cannot conceive in what way their operations have been disastrous. It is quite true that they have been compelled to supply in restricted areas, but surely the fault in this respect lies more particularly with those Government Departments which are so tightly bound with red tape and to which I have already referred.

Many of the municipal undertakings, if not all, would have willingly extended beyond their areas if they had been allowed to do so, but Government Departments have been too apt to listen to the pleadings of smaller urban and rural councils, whose opposition has merely emanated through jealousy.

* *Journal I.E.E.*, 1919, vol. 57, p. 31;

There may have been, of course, some cases where the activities of certain authorities have not been such as one would desire, but I think it will be agreed that municipalities generally have played a great part—particularly during the period of the war. From this point of view the paper * by Mr. Arnold B. Gridley (Director of Electric Power Supply), in conjunction with Mr. A. H. Human, is, in my opinion, a splendid testimonial to what municipal authorities have done and the results that have been obtained.

A fair comparison as between company and municipal undertakings was not made when evidence was submitted to the various committees set up by the Government to inquire into this important matter, and the conditions relating thereto are very different in the two cases. In the one case, provision for proper depreciation and obsolescence of plant is sometimes disregarded in order to obtain dividends and maintain the market values of shares, and to satisfy temporarily those who have invested their money, but in the other case, that of municipal undertakings, there is no option. The total capital debt has to be liquidated within a given period of time.

In order to make a comparison that would be fair to both, I consider that gross profits in each case should be shown after allowing for management charges, etc., and then how such profit has been disposed of. It might be shown that the amounts set aside by municipal undertakings, as interest on loans and for redemption of capital by means of sinking fund instalments, would exceed the amounts distributed in the form of dividends by companies.

However, the Bill—if carried into effect in the proper way—should be of considerable advantage to all.

There is one matter which appears to be perfectly clear, namely, the impossibility of standardizing one frequency. It may be necessary to standardize merely in different areas, in consequence of the enormous amount of capital already expended in such areas, not only in generating plant, but in substations and upon consumers' premises.

Ways and Communications Bill.

The setting up of a Ministry controlling Transport generally, provided under the Ways and Communications Bill, is an important step and, in my opinion, a step in the right direction.

There may be objections to giving carte blanche to so enormous a Department as this is likely to be, but, after all, transport directly affects the trade of the country and it is essential that all forms of transport should be properly co-ordinated.

The many instances of companies competing with local authorities will have to be removed, and all must agree to work together for the good of the industry generally.

Many of us are conversant with the difficulties regarding the interchange of running, where two systems of tramways adjoin one another; and the feeling of jealousy between one authority and another, whether municipal or company, which has been allowed to prevail in the past and which, in my opinion, has undoubtedly adversely affected the interests of both, will have to be removed.

Further, I am of opinion that the Ministry of Ways and Communications will be of advantage to those at present responsible for the provision of transport facilities in local areas.

Regarding the question of transport facilities, I read a paper before the Municipal Tramways Association at their Conference in 1917, having particular reference to the development of the tramways industry, and even at that time I had in mind something similar to what will in my opinion be likely to result from the Bill. I pointed out that upon the termination of the war, with the railways suffering as a result of depletion of rolling stock and engines, great openings for tramways and transport undertakings generally would arise, and I also suggested that the railways would later be used for the long-distance traffic, whilst tramways or light railways would cater for all the less important traffic. I suggested that canals and waterways would probably be taken over and converted to either electric or steam haulage, in order to relieve the pressure upon the railways.

During the period of the war, we have learnt the lesson of the advantages of the cultivation of food. We have also had opportunities of appreciating the difficulties of transporting such food from where it is produced to the important centres, from which it is either distributed or disposed of entirely. All these difficulties have arisen as a result of restrictions previously imposed upon municipal and company undertakings, willing to cater for the same, but not allowed to do so.

The development of tramways and other forms of transport will certainly be necessary in connection with housing schemes, to enable the working classes to obtain better enjoyment out of life by living further than they do at present from their centres of work, and such extensions as tend towards the development of breathing spaces and residential districts.

They will have a direct effect upon the development of factories and works, which must necessarily be set up if we are to prevent ourselves slipping back into those hateful conditions that prevailed prior to the war.

I think we can reasonably look forward to seeing at some future date—I hope not far distant—towns and cities generally, both large and small, interconnected in this way. Not only so, but that the time must come when important tramway undertakings will have to be linked up by means of sidings to works connected with important industries, so that during many of the 24 hours when the transport of the ordinary passenger is not required, the lines and equipment can be used for the transport of goods.

All this will undoubtedly tend towards conserving coal supplies for more important purposes.

If the setting up of a Ministry such as this does nothing else but remove the system of red tape which has previously prevailed, it will have done a very good work and one to which we are looking forward with the keenest possible interest.

The urgent necessity for better and greater development in road transport has been more prominently

* *Journal I.E.E.*, 1919, vol. 57, pp. 406 and 541.

brought to the notice of people generally during the recent railway strike.

The electrification of railways is a very important feature of the Bill, distinct entirely from what I have reason to think will take effect in course of time, viz. the construction of special transport roadways which will be looked upon as main arteries throughout the country for the rapid transport of goods.

Roughly speaking, there are some 24,000 miles of railway in the United Kingdom, and a very low estimate based upon pre-war figures would show that at even £20,000 per mile the cost of electrification would not be less than some 400 million sterling. Upon this basis it is not difficult to imagine what the present-day cost is likely to be. Whatever such cost might be, however, it must necessarily include proper provision for power houses, railways, substations, transmission lines, and all other work incidental to the electrical operation of railways, and when it is borne in mind that the railway capital at the moment is approximately 1,300 million pounds sterling, and is not now productive of dividends owing to advances in wages and cost of material. The addition of probably more than one half to this capital must necessarily be a very serious matter, but it is assumed that, as a result of electrification, considerable economies will be effected in the operation of our railways and will have the effect of counteracting to some effect the increase in capital expenditure.

If the railways, as we have reason to think, are to be eventually handed back to the companies previously controlling them, there may be some difficulty in raising the necessary additional capital, unless financial relief is afforded by the Government.

Let me at once say that I hope both these Bills—the Electricity Supply Bill and the Ways and Communications Bill—will be entered upon the Statute Book at an early date, in order that the necessary works shall be put in hand without any loss of time.

Coal.

This is a subject about which we are all very much concerned.

A Coal Commission was set up by Parliament to investigate thoroughly the conditions under which coal was produced. We have all probably read the proceedings of the Commission with considerable interest, and it is now felt by a great number that it would be a national calamity if the coal industry were to be nationalized.

I think I may safely suggest that the Constitution of the Commission was not what any business man would recognize; and I also think we are all agreed that an industry of such importance as the coal industry is better left in the hands of private enterprise, if and so long as proper means are provided whereby fair wages and reasonable conditions of employment are secured to the workers. There is a considerable amount of satisfaction in the knowledge that the Government, for very obvious reasons, more particularly those provided quite recently by the railway strike, are not so sympathetically inclined towards the question of nationalization as they might have been previously.

The electrical industry depends, almost exclusively, on ample and cheap supplies of coal, and the undertaking with which I am connected is to-day paying 33s. per ton for coal for which we paid 13s. prior to the war. It is not a difficult matter to appreciate the effect that the price of coal has upon the cost of production, and the necessary increases in charges paid for supplies, and yet we talk about the development of the use of electricity generally throughout the country, whilst all the time such development is being made more difficult in the way I have indicated.

The restricted output of coal has also made it impossible to put in hand those works which are so necessary owing to the heavy dilapidations that have taken place during the period of the war. Is it altogether surprising, although it is regrettable, that in some cases we find orders being placed abroad?

Many of us feel that if left alone the greater number of the workers of this country would use better judgment; and we can only hope that the formation of Industrial Councils and District Councils will have the desired effect, but they will be of no use whatsoever unless those controlled by them honestly abide by their findings.

Research Work.

This is a matter which is deserving of the most serious consideration. A very interesting Report has been submitted by a Committee of the Privy Council, dealing with Scientific and Industrial Research. The Report clearly states that there is no closed door to research work. It is open to all who, by way of livelihood or hobby, direct skilled attention to the subject, as well as to those whose present concerns are fixed in the laboratory.

There is a common idea that the discoveries and inventions which tend to facilitate manufacture and to augment the conveniences of daily existence come by chance. The fact is, that even where the element of fortune enters into the case, the mind of the discoverer or inventor has been prepared for its revelation by prior study and active interest, and that the usual avenues of discovery and invention lie through patient work in the laboratory or experimental workshop.

These augmentations of learning are augmentations of public wealth. In the view of many, the persons who produce these results are the chief benefactors of the species.

In some instances, the exploitation of discoveries and inventions was deprecated, in the public interest, in past years, but those days are past. Competition compels the manufacturer to avail himself of every improvement in production which offers itself, and in many instances the manufacturer employs experts for no other purpose than research work. If the competitive system were displaced by a system of State monopoly, the incentive to research and the exploitation of discoveries and inventions would vanish.

One of the interesting features of the Report of the Privy Council Committee is that relating to the formation of Research Associations. Minds are quickened by contact with minds; active interest is reinforced by competition and emulation; and effort is saved by the

avoidance of duplication and all dead avenues of inquiry.

There was no time when the need for research work was greater than at present. We need more economical use of coal, the discovery of new sources of heat and power, better utilization of national resources and waste products. There is the need of having our industries placed more generally upon a scientific basis, and we have need to produce and employ a much greater number of efficient, trained workers for both production and research.

Whilst Germany has been beaten on the field of battle, she is not going to remain content by any means and has put forward every effort to recover and, if possible, strengthen her position commercially. There is no doubt that in Germany an enormous amount of research work must have been carried on, resulting in most wonderful improvements in war machinery, which have been so freely used. It would be distinctly satisfactory if those engaged upon research work could make known their discoveries to all others, in order that they might have the advantage in some cases of some particular discovery that was of no commercial value to the individual discovering it.

Research work has not had that amount of encouragement in past years which it has deserved. I recently turned up a cutting from the *Electrician* of the 4th April, 1914, in which attention is drawn to the remuneration paid to men who are supposed to be highly skilled, possessed of university degrees, etc., and who were to be responsible for the training of the minds of young people, and to whom a salary of £150 per annum, rising to £240 according to experience and qualifications, was offered. This salary was aptly compared with the wages paid to a non-skilled individual, sweeping streets in London, and in receipt of at least £3 5s. per week! Yet this salary was offered by a wealthy concern.

Of course, there would be many candidates for such positions, but in most cases it would be found that the candidates themselves would be very much in need of training.

Technical Staffs.

In conclusion, there is one matter of the greatest importance to which I should like to refer, viz. the salaries of technical staffs.

I am of opinion that local authorities and employers generally have not appreciated the members of their technical staffs at their true value. This has resulted in these men organizing themselves in the same way as the ordinary employees have done for a number of years past; and instead of graciously granting the additional remuneration more fairly representing the value of these people, employers are now compelled to do so. This, to my mind, is a misfortune in more ways than one. At one time, whilst the employees had the full amount of war bonus or war wages conceded to them by Government Departments and in connection with which employers had no option whatsoever, it was generally found that the technical members of the staffs were in receipt of a very much less bonus and their positions relative to the other employees were not maintained.

Personally I must confess that I welcomed the formation of the Electrical Power Engineers' Association, although I was strongly of opinion that it was most unfortunate that such a thing should have been necessary.

It is in cases of trouble that we have to fall back upon our technical staffs, and there are many instances where employees, dissatisfied with their conditions, have not hesitated to withdraw their labour, the responsibility of keeping things going being undertaken by the technical staff. In such cases as these even their services have not received that amount of recognition which they have deserved.

There is another reason why the formation of the Electrical Power Engineers' Association has been welcomed as it has been. Certain trade unions have threatened a withdrawal of labour unless the members of the staff join their unions. If such a thing had been left possible, the results would have been lamentable.

NORTH MIDLAND CENTRE: CHAIRMAN'S ADDRESS

By W. M. SELVEY, Member.

(*Address delivered at* LEEDS, 11 *November*, 1919.)

I have to express my great thanks to the members of this Territorial Centre for the honour they have done me by electing me to be the Chairman for this Session.

A comparative stranger from further North I have experienced to the full the heartiness of a Yorkshire welcome. I think I may say that I have followed pretty closely the proceedings of this Centre for the last 5½ years during which I have been a resident in Sheffield, and it has given me great satisfaction to see the undoubted signs of growth and progress which culminate this year in the re-establishment of meetings in Sheffield as a Sub-Centre from the parent Centre at Leeds. Our membership is rapidly increasing, and there are such a considerable number of members now residing in and around Sheffield that the decision of the Council to cater for them specially is very welcome.

It is inevitable that a Chairman's Address should contain many references to topical events, but the principal topic on which I could have dwelt most, viz. the new national proposals in the Electricity Supply Bill now before Parliament is, at the time of writing, an unsuitable subject as it is *sub judice*. Suffice it to say that no subject has so stirred up the whole of the members of the Institution, nor ever before has the action of the Institution been so thoroughly decided.

At the time of writing, there are great hopes that the hindrances which have so long affected the general situation are likely to be removed, and the fact that one of our Past-Presidents, Sir John Snell, is the Chairman designate of the new Electrical Commissioners, gives great confidence in the future.

It is natural to refer to the happy ending of the great War and the success of our gallant soldiers in overcoming the most highly organized military machine the world has ever seen. We now welcome very heartily many of our members who have returned to us from the Army.

While these and other members have had the supreme privilege of serving at the Front, there have been many war-time activities of the members remaining at home. I wish to refer pointedly to the work of the local members which has resulted in that excellent report known as the "Report of the Yorkshire Electric Supply Linking-Up Committee." This Report, which is accompanied by an excellent map, is not yet published, but it is hoped that ultimately the Report will be accessible to all members and that they will then see how carefully matters connected with Yorkshire have been considered.

It is necessary also to refer to the enormous progress which has been made in three of the district undertakings. The phenomenal expansion of the Sheffield output from that of an ordinary sized undertaking to an output of 172,000,000 units per annum is almost a romance in itself. Detailed figures have been widely quoted and it is hardly necessary to mention them again. I hope that members of the Centre will some time have an opportunity of visiting both the Sheffield stations when the newest one is completed.

We are also very proud in referring to the first station on what is now known as super-station lines, viz. that at Rotherham, where is now being installed the largest set (30,000 kw.) yet built for this country. The Yorkshire Electric Power Company have also made most effective progress, not only in largely extending their generating capacity but also in wonderfully extending their system of overhead mains. I think I am correct in saying that there is no other system in this country which can show anything like such progress in this direction. I have some hopes that much information with regard to these three schemes will come before the members in one shape or another during this Session, although at the moment the actual form for presentation is not settled. The Leeds extensions are also somewhat noteworthy. Other large extensions have been projected, but War circumstances have delayed them in many cases. Many members other than the signatories of the Linking-Up Report will hardly realize that in Yorkshire in 1918 the generated units were over 520,000,000, with a maximum demand of over 160,000 kw. Personally, I expect that during the next 10 years Yorkshire, with its woollen, steel, and coal industries, will become the most highly organized electrical area in any part of the world.

Another phase of activity in which the members of the Centre have been largely employed is that of giving assistance to the Coal Controller in connection with the re-distribution scheme and the coal economy campaign. This assistance was willingly given to the former Technical Adviser to the Coal Controller, Mr. David Wilson, whose name is so well known among electrical engineers, and followed his decision that the electrical engineers of the country were the best-qualified body to deal with all questions relating to the economy of fuel. While the assistance ultimately found necessary had to be drawn from many classes of engineers outside the Institution, Mr. Wilson's considered opinion was that his original judgment had been amply confirmed. There were over 25 of the members of this Centre who assisted in this voluntary work, and as one who had the privilege of joining with them in this work, I can express my great admiration of their technical ability and keenness.

It was very curious to me that some of our members who have by force of circumstances been left in charge of small municipal undertakings, and whose scope has been limited in consequence, due as we all know to early legislation, have proved under other circumstances how ably they can handle a much wider sphere of influence when given the opportunity. On the other hand the experience itself has been most educative,

and as I have already said in public, should the principle of nationalization become more and more extended the electrical engineer of a district could, with a maximum advantage to the community, become responsible for the whole user of power in his district, either if such power is taken from the public mains, or is generated by a private plant whether by steam or gas. Whether such an ideal is utopian or not I cannot say, but such a scope would lead to balanced thought and a proper perspective with regard to the interests of the community.

If the members had previously been only half convinced of the value of a generous electricity supply to the community they must have become wholly convinced by their experience in this work. From their specialized point of view, the waste of fuel, the carelessness, indifference, and the ignorance of power users in many lines of industry were most disturbing. While many of the larger industrial undertakings with private plant are exceedingly well equipped, not only are there many small power users who are scandalously inefficient, but other industries using large quantities of fuel, and who have little use for power, are still more wasteful in most cases. The training of the electrical engineer in power generation has been shown to be exceedingly helpful in dealing with all questions where the combustion of fuel is concerned, whether for power or other purposes.

The past year is especially notable with regard to influence on the future of the Institution arising from the efforts of our most able Past-President, Mr. C. H. Wordingham, C.B.E. Members have been most intensely interested in his grand ideas for the future of the Institution. Not the least valuable side of these is that it has set all the members thinking, not always necessarily on the same lines. It has given us all a new idea of what the Institution may be and, may I say, shall be in the lives of all its members.

Arising out of my experience of this Centre I am struck with the wealth of enthusiasm, knowledge and goodwill which is shown by our younger members and which makes me long to find some way of turning this sterling gold into channels that will enure for the benefit of the Institution, the profession, and the whole community. It is most necessary that it should be guided. The question is: How? My own personal experience is that we have need for more ideals to hold together these younger members. No organization can live without authority, but in this case the authority must be moral authority conceded by the members voluntarily because they believe that the holders of this authority will use it for the advancement of agreed ideals. We must continually keep before our minds the fact that an ideal easy of attainment is not an ideal worth fighting for. A true ideal must be painfully wrought out step by step.

A tremendous impetus to the coherence of the members has been given by the inspiring presidency of Mr. Wordingham, and much has been done. We cannot always expect to progress at this rapid rate, and we must bear in mind that in order to keep up anything like the rate of progress we must all join in making our new President realize that he has the whole-hearted feeling of the members behind him. It used to be the cry of the younger members: "What does the Institution do for us?" This cry is now out of date, and in any case was based on a misunderstanding of how a body becomes powerful. In our case it can only become powerful when the enthusiasm and driving power of the younger members is welded with the judgment and experience of the older members.

I am going to venture with great diffidence to make a few remarks on what the older members and younger members can do for each other; what both can do for the Institution, and what the Institution can do for them. In my opinion the older members can do much for the younger members by giving them help and advice, not merely on how to get on, but how to make the best use of the opportunities they now have. It is so very much easier for the experienced members to see the opportunities than for the younger ones to recognize them. The junior members can help the senior members by never relaxing their enthusiastic attentions to their duties. The outlook of each junior member is very largely and legitimately that of desiring to better his position, but he must also equally think of how to fit himself for the position when it comes.

It is the common experience of the older members, myself included, that when a particular position is required to be filled, while there are applications almost without limit, it is exceedingly difficult to select the man who exactly fills the position from the point of view of the engineer making the appointment. The younger members should study what they are able to admire in the older members and to meditate on what qualities make for success. They will be rather surprised in many cases on reflection how many of these turn more on high personal character than on abstruse technical knowledge, and if they are honest with themselves they will also be rather surprised at the amount of self-discipline and even self-sacrifice they will need to exercise to develop these same qualities in themselves. Nevertheless, no young man has a right to excuse himself from making these efforts as he knows that from his associates must be drawn those who are to occupy positions of importance in the future, especially having in mind the wider and wider fields which are now opening out to electrical engineers.

And now a short word as to how both can help the Institution. There is no biblical tale which has more point in this direction than that of "Naaman the Leper." I lay it down fearlessly that the most important thing of the whole matter is that all members must attend the meetings regularly. I would wish that they all could develop a conscience which tells them that every Institution meeting is a serious and a primary engagement demanding sacrifice of time and, perhaps, money. The very type of member who says the meeting is no use to him or not worth attending will find the whole Institution a new thing to him if he himself comes regularly and faithfully. Whatever he fails to find, he will find a growing fellowship among the members.

Lastly, a word as to what the Institution can do

for us all. It would be impossible to refer to the Institution's many activities which are multiplying and becoming many sided every day, but I venture to suggest that the Institution as á corporate body is and always will be the origin of education in its highest sense. Much is now done in this direction, and more can be done if the members will formulate suggestions which can be put before the Local Committees and transmitted by them to the Council. The work of the Council will always be helped and stimulated if they feel they are in close touch and sympathy with an agreed body of members and are fully provided with information.

It is hardly necessary to emphasize that the Council is the only body which can co-ordinate and put into practice the outcome of any such suggestions.

On the subject of education I am tempted to say much, based not only on strong feelings, but on my own personal experience of technical education. So much has been said of the training of the engineer in his student stage that I think attention should be now drawn to the continued training of engineers for long years after they have left their college or the works where they have served their apprenticeship.

We are all familiar with the system whereby naval and military officers who desire to be efficient can return over and over again independent of rank and age to take technical courses at their headquarters. The Institution provides many highly technical papers written by experts and masters of their subjects, much of the material of which is quite beyond all but a few of the junior members and perhaps many of the senior members. In the course of such papers we find assumptions made—quite justifiable—and important information known only to a few, skipped over almost without notice in order to shorten the paper to consideration of the main matter. It is perhaps often just these points which would most interest and instruct many of us. While they would be out of place in the main paper it would be a great advantage if notes on such points with reference to other important papers, text-books, and the like, were contained in an appendix at the end of the paper. Many of these points would be suitable as a basis of examination papers for the Associate Membership Examination. The Council might, with a view to adding to the interest of the younger members and building up the Institution of the future through them, arrange for suitable points to be selected and even go the length of arranging correspondence between the junior members and the authors of papers on points on which further information was required.

The natural modesty and diffidence of the best type of younger member will always hinder him from either joining in the discussion at the meetings or asking questions of the authors of the papers, and yet this type of member is often the most earnest searcher after truth. Older members must always remember that all the accumulated information and experience which we have has to be retransmitted to the coming generation.

I should here like to protest against the cheap sneers that are often indulged in by older members with regard to what is called "theory," and their continual cry that "experience" or "practice" is what is necessary. Much of this, where having some foundation in reason, is due to a wrong use of the term "theory" to describe many hastily conceived and ill-considered "hypotheses" which have been put forward from time to time by inquirers groping in the dark. Hypothesis is the very opposite to theory. It is the attacking of ignorance with an untried sword and armour, highly necessary but very difficult. True theory on the other hand is simply highly condensed experience and, as such, should be honoured and kept apart from hypothesis.

Younger members learn the language of theory without at all understanding the experience of which it is the summation, and the real use of experience is to train the younger members to understand what theory really amounts to in actual material facts so that they may be enabled to make a good fight with the ignorance which is yet to be conquered. The man who can conquer this ignorance is the real practical man of the future, and not he who has been described by some "academic" person as "the man who faithfully repeats the mistakes of his predecessors."

To return, however, to our subject, not only do I think the younger members want this help in grasping the foremost questions of the day, but I think the older members require much help in order to be kept in touch with the ever-widening circles of knowledge, all of which are being developed under the ægis of the Institution. I can conceive in the future that no Session will be considered complete which does not include at least two lectures per year before each Territorial Centre, one from a distinguished professor, typified to-day, say, by Sir Joseph Thomson, who will give the members some résumé of the progress made in pure science such as affects the interests of the members, and further to this, another lecture given by the experimental type of research engineer who will give some account, say, of the work done at the National Physical Laboratory and of the various activities of the Research Committee.

While, of course, such matters can be dealt with by communications to the *Journal* and by Reports, this mode of imparting knowledge will never be equal to the spoken word. The joint impression on the brain by the simultaneous appeal to the eye and the ear will always be much more vivid than the appeal to the eye alone. Moreover, the spoken communication is always in language "more easily to be understanded of the people" than is the more formal language of an official communication. The Institution has, of course, done much in this line already, but without, I venture to think, a general body of the members quite realizing the significance of the matter.

In conclusion, I must refer to the very able papers which have been contributed to the "Proceedings" of the Institution this year by our members Mr. Yerbury and Mr. Shaw. Both of these papers have received clear recognition of their value from the members. I should like to add a short technical note (see Appendix 1) on my own account with regard to the subject of Mr. Shaw's paper on "The Use of High-Pressure and High-Temperature in Large Power Stations." * I have kept very closely to the same figures that Mr. Shaw has

* *Journal I.E.E.*, 1919, vol. 57, p. 73.

used, so that this short note of my own may be read as an appendix to that paper, and I hope that though rather technical it will be of interest to some of the members. I have termed the calculations "High Pressure and High Temperature Steam with Interheating for Power Generation."

APPENDIX 1.

CALCULATIONS RELATING TO HIGH PRESSURE AND HIGH TEMPERATURE STEAM WITH INTERHEATING FOR POWER GENERATION.

The subject of interheating is of some interest at the present time because it is a means of getting a higher thermodynamic efficiency without resorting to higher temperatures and pressures, that is without putting further stresses on the materials employed. The following calculations have been made with a view to seeing what gain of efficiency is possible, and they are in particular an extension of the valuable figures given in Mr. Shaw's paper.*

The same general figures of temperatures corresponding to high pressures have been taken as in Mr. Shaw's schedules. All the steam pressures are expressed in absolute measure, the highest taken being 500 lb. The highest temperature taken is one also used by Mr. Shaw, viz. 688° F. While temperatures slightly higher than these may ultimately be employed, it is thought that this is sufficiently high to cover a ground which may be of interest within the next stage of power developments. As regards vacuum, all modern power stations in future will fall within the limits chosen of 28 inches (that is, an absolute pressure of 2 inches) and 29·1 inches (that is, an absolute pressure of 0·9 inch).

The tables given below are simply figures defined by the nature of steam, and are independent of any form of apparatus. They can therefore be used in any particular case by taking into account the efficiency of the apparatus. The schedules are numbered 1 to 7, and are accompanied by seven diagrams illustrating some of these tables. In Schedule 1 the data are given relating to diagram efficiencies obtainable with steam initially at 500 lb. per square inch absolute, total temperature 688° F., where the steam after expanding and doing work to certain selected pressures is again reheated to the original temperature and then further expanded down to vacuum pressures.

The figures of course represent what could be obtained were it possible to build a heat engine of 100 per cent mechanical efficiency, and if there were no losses of pressure in conveying the steam to be reheated from and to the engine. It is convenient to refer to them as "cycle" efficiencies.

It will be quite easy to find the influence of such losses as are inevitable by means of curves drawn from the data given in this and the other schedules. The schedule gives a column in which the obtainable efficiencies are all compared with plain expansion straight from the full pressure to vacuum, the comparison from vacuum to vacuum being preserved. The first schedule shows that the best circumstances for interheating are by expanding to a pressure somewhere in the neighbourhood of 200 lb. per square inch before the reheating, and that the possible gain in efficiency is of the order of $2\frac{1}{2}$ per cent.

Schedule 2 takes the same circumstances from rather a different point of view, namely, that while expanding to the same set of pressures the steam is not reheated to its original temperature but only to its original superheat. There are certain reasons for making this selection which could not be gone into here except to say that all practical cases must lie between these two limits. Under these circumstances Schedule 2 shows that the best pressure for a single interheat is somewhere above 200 lb. and that the possible gain in efficiency is of the order of $1\frac{1}{4}$ per cent.

In Schedule 3 are given calculations which show the effect of twice interheating the steam, i.e. making three separate expansions, the steam being reheated after each expansion to its original temperature. The calculations show that there is a fairly wide range of choice for two interheats for which the efficiency remains sensibly constant, the most favourable of these conditions shown being an expansion first to 215 lb., reheating, and then an expansion to 70 lb., and further reheating with a final expansion from 70 lb. to the vacuum pressure. These calculations show a possible gain in efficiency over plain expansion of about $4\frac{1}{2}$ per cent.

Schedule 4 is derived from the other schedules for the purpose of drawing out the connection between the value of interheating and the initial pressure. The figures given show very clearly that the value of interheating is greater in proportion as the initial pressure is lower. At the top of the list the expansion from 500 lb. with an interheat to the original temperature at 150 lb. shows a gain for plain expansion from 500 lb. of only 2·4 per cent. At the bottom of the table, steam originally at 150 lb. interheated at 50 lb. to the original temperature of 688° F. shows a gain over plain expansion from 150 lb. of 7·2 per cent. This draws attention to the value of pressure, and in Schedule 5 the figures are collected from these aforegoing schedules which show the value of pressure alone for the constant top temperature.

It is necessary to take some basis for comparison and in this schedule the absolute pressure of 215 lb., that is of 200 lb. gauge, is taken as a basis. The figures show that at 500 lb. the gain is a matter of 11 per cent, whereas at 70 lb. pressure (there is a large amount of such steam yet used in this country) there is a deficit of 15 per cent.

Schedule 6 gives the same set of figures, but in this case with the superheat kept at the constant figure of 219·3 degrees F. This table somewhat clearly brings out the value of pressure because the superheat is kept constant, whereas in Table 5 the superheat necessarily decreases as the pressure rises, the steam being maintained at the constant top temperature. In Schedule 6 it is seen that the gain of 500 lb. over 215 lb. is as much as 13 per cent.

* Loc. cit.

Schedule 7 collects together the main efficiencies of the Schedules and they are compared with the efficiencies to the diagrams which show much more quickly what these variations of efficiency mean.

SCHEDULE 1.

Data relating to Diagram Efficiencies obtainable with Steam Initially at 500 lb. per sq. in. abs. pressure; 688° F. Total Temperature; with One Interheating to 688° F. before Final Expansion (H_0=1355·9 *therms*).

Stage Pressure for One Interheat to 688° F.	Final Expansion Pressure Vacuum (Barometer 30 in.)	Available Work to First Stage Pressure	Available Work (after Interheating) to Final Pressure	Total Available Work, both Stages	Total Heat (H$_1$) after First Stage Expansion	Heat to be added for Reheating to 688° F.	Total Heat of Reheated Steam (HK$_1$)	Summation Heat less Heat in Feed	Thermodynamic Efficiency $\frac{\Sigma(W)}{\Sigma(H)}$	Equivalent Carnot Temperature, $\frac{\Sigma(W)}{\Sigma(\phi)}$	Gain in Economy due to One Interheat
lb. per sq. in. abs.	Hg. in.	therms	therms	therms	therms	therms	therms	therms	per cent	° F.	per cent
365	28·0	36·9	441·9	478·8	1319·0	44·2	1363·2	1331·2	35·96	415·8	1·3
365	28·5	36·9	456·3	493·2	1319·0	44·2	1363·2	1340·6	36·79	412·6	1·2
365	29·1	36·9	480·9	517·8	1319·0	44·2	1363·2	1356·4	38·18	406·6	1·1
280	28·0	66·2	428·5	494·7	1289·7	78·1	1367·8	1365·1	36·24	420·6	2·0
280	28·5	66·2	443·2	509·4	1289·7	78·1	1367·8	1374·5	37·06	416·2	1·9
280	29·1	66·2	468·4	534·6	1289·7	78·1	1367·8	1390·3	38·45	410·2	1·8
215	28·0	93·3	414·2	507·5	1262·6	108·7	1371·3	1395·7	36·37	421·4	2·4
215	28·5	93·3	429·3	522·6	1262·6	108·7	1371·3	1405·1	37·21	418·4	2·3
215	29·1	93·3	455·0	548·3	1262·6	108·7	1371·3	1420·9	38·59	412·2	2·2
200	28·0	99·9	410·4	510·3	1256·0	116·0	1372·0	1403·0	36·39	421·6	2·5
200	28·5	99·9	425·5	525·4	1256·0	116·0	1372·0	1412·4	37·20	418·2	2·3
200	29·1	99·9	451·3	551·2	1256·0	116·0	1372·0	1428·2	38·60	412·4	2·2
150	28·0	127·2	394·1	521·3	1228·7	146·0	1374·7	1433·0	36·38	421·6	2·4
150	28·5	127·2	409·6	536·8	1228·7	146·0	1374·7	1442·4	37·21	418·4	2·3
150	29·1	127·2	435·9	563·1	1228·7	146·0	1374·7	1458·2	38·62	412·6	2·3
100	28·0	162·3	370·8	533·1	1193·6	183·8	1377·4	1470·8	36·24	420·3	2·0
100	28·5	162·3	386·6	548·9	1193·6	183·8	1377·4	1480·2	37·08	416·6	1·9
100	29·1	162·3	413·7	576·0	1193·6	183·8	1377·4	1496·0	38·51	411·2	2·0
90	28·0	170·9	364·6	535·5	1185·0	192·9	1377·9	1479·9	36·18	419·0	1·8
90	28·5	170·9	380·6	551·5	1185·0	192·9	1377·9	1489·3	37·03	415·8	1·8
90	29·1	170·9	407·7	578·6	1185·0	192·9	1377·9	1505·1	38·45	410·2	1·8
80	28·0	180·3	357·7	538·0	1175·6	202·9	1378·5	1489·9	36·11	418·0	1·7
80	28·5	180·3	373·8	554·1	1175·6	202·9	1378·5	1499·3	36·96	415·0	1·6
80	29·1	180·3	401·3	581·6	1175·6	202·9	1378·5	1515·1	38·39	409·4	1·7
70	28·0	191·0	349·8	540·8	1164·9	214·1	1379·0	1501·1	36·02	416·8	1·4
70	28·5	191·0	366·0	557·0	1164·9	214·1	1379·0	1510·5	36·88	414·0	1·4
70	29·1	191·0	393·7	584·7	1164·9	214·1	1379·0	1526·3	38·31	408·4	1·5
Plain Expansion	28·0	0	457·11	457·11	—	—	—	1287·0	35·51	409·8	0
Plain Expansion	28·5	0	471·57	471·57	—	—	—	1296·4	36·37	406·8	0
Plain Expansion	29·1	0	495·6	495·6	—	—	—	1312·2	37·76	400·6	0
*d(28) Plain Expansion	28·0	457·11	0	457·11	—	—	—	1771·0	25·81	—	—
*d(28·5) Plain Expansion	28·5	471·57	0	471·57	—	—	—	1794·9	26·26	—	—
*d(29·1) Plain Expansion	29·1	495·6	0	495·6	—	—	—	1834·7	27·61	—	—

* Special case to accompany Figs. 4, 5, and 6, to show limiting conditions with reduction of pressure of interheating; this being now P+d P, where P=vacuum pressure.

obtainable with a perfect fluid between the same limits of temperature. Having thus drawn attention to the bare figures and their calculations, we may turn

Fig. 1 (page 38) is an ordinary temperature-entropy (T ϕ) diagram exactly as given in Mr. Shaw's paper. The area bounded by the lines marked "Water,"

"Evaporation," "Superheat," the vertical line from the highest point of the superheat and the condensation line, represents to scale the available work. The rectangle between this area and the absolute zero represents the heat rejected to the condenser. The efficiency is therefore the "work area" divided by the "work area" plus the "heat rejected area." Were water a perfect fluid from a heat engine point

SCHEDULE 2.

Data relating to Diagram Efficiencies obtainable with Steam Initially at 500 lb. per sq. in. abs. pressure; 688° F. Total Temperature, with One Interheating to restore Original Degree of Superheat (219·3 Degrees F.) before Final Expansion (H_o=1355·0 *therms*).

Stage Pressure for One Interheat to 219·3 F. Superheat	Final Expansion Pressure Vacuum (Bar. 30 in.)	Available Work to First Stage Pressure	Available Work (after Interheating) to Final Pressure	Total Available Work, both Stages	Total Heat (HE_1) after First Stage Expansion	Heat to be added for Reheating to 219·3° F. Superheat	Total Heat of Reheated Steam (HR_1)	Summation Heat less Heat in Fee	Thermo dynamic $\Sigma(W)$ Efficiency $\Sigma(H)$	Equivalent Carnot, Temperature, C (t)	Gain in Economy due to One Interheat
lb. per sq. in. abs.	Hg. in.	therms	therms	therms	therms	therms	therms	therms	per cent	° F.	per cent
365	28·0	36·9	433·3	470·2	1319·0	26·8	1345·8	1313·8	35·80	413·8	0·8
365	28·5	36·9	447·6	484·5	1319·0	26·8	1345·8	1323·2	36·61	410·2	0·7
365	29·1	36·9	472·0	508·9	1319·0	26·8	1345·8	1339·0	37·99	403·8	0·6
280	28·0	66·2	413·4	479·6	1289·7	47·8	1337·5	1334·8	35·92	415·4	1·2
280	28·5	66·2	427·9	494·1	1289·7	47·8	1337·5	1344·2	36·76	412·2	1·0
280	29·1	66·2	452·6	518·8	1289·7	47·8	1337·5	1360·0	38·15	406·0	1·0
215	28·0	93·3	393·6	486·9	1262·6	66·8	1329·4	1353·8	35·96	415·8	1·3
215	28·5	93·3	408·3	501·6	1262·6	66·8	1329·4	1363·2	36·80	412·8	1·2
215	29·1	93·3	433·3	526·6	1262·6	66·8	1329·4	1379·0	38·19	406·6	1·1
200	28·0	99·9	388·2	488·1	1256·0	71·2	1327·2	1358·2	35·95	415·8	1·2
200	28·5	99·9	402·9	502·8	1256·0	71·2	1327·2	1367·6	36·78	412·6	1·1
200	29·1	99·9	428·1	528·0	1256·0	71·2	1327·2	1383·4	38·16	406·2	1·1
150	28·0	127·2	367·0	494·2	1228·7	90·0	1318·7	1377·0	35·89	414·8	1·0
150	28·5	127·2	381·9	509·1	1228·7	90·0	1318·7	1386·4	36·71	411·6	0·9
150	29·1	127·2	407·4	534·6	1228·7	90·0	1318·7	1402·2	38·13	405·8	1·0
100	28·0	162·3	337·0	499·3	1193·6	113·4	1307·0	1400·4	35·65	411·8	0·4
100	28·5	162·3	352·3	514·6	1193·6	113·4	1307·0	1409·8	36·52	409·6	0·4
100	29·1	162·3	378·4	540·7	1193·6	113·4	1307·0	1425·6	37·93	403·0	0·4
90	28·0	170·9	329·3	500·2	1185·0	119·1	1304·1	1406·1	35·58	410·8	0·2
90	28·5	170·9	344·7	515·6	1185·0	119·1	1304·1	1415·5	36·44	407·8	0·2
90	29·1	170·9	370·9	541·8	1185·0	119·1	1304·1	1431·3	37·85	402·0	0·2
80	28·0	180·3	320·8	501·1	1175·6	125·2	1300·8	1412·2	35·48	409·4	0·1
80	28·5	180·3	336·2	516·5	1175·6	125·2	1300·8	1421·6	36·33	406·2	0·1
80	29·1	180·3	362·5	542·8	1175·6	125·2	1300·8	1437·4	37·77	400·8	0·0
70	28·0	191·0	311·0	502·0	1164·9	133·9	1298·8	1420·9	35·33	407·4	0·5
70	28·5	191·0	326·6	517·6	1164·9	133·9	1298·8	1430·3	36·19	404·4	0·5
70	29·1	191·0	353·1	544·1	1164·9	133·9	1298·8	1446·1	37·63	398·8	0·3
Plain Expansion	28·0	0	457·11	457·1	—	—	—	1287·0	35·51	409·8	0
	28·5	0	471·57	471·6	—		—	1296·4	36·37	406·8	0
	29·1	0	495·6	495·6	—	—	—	1312·2	37·76	400·6	0
*d(28) Plain Expansion	28·0	457·11	0	457·1	—	—	—	1660·4	27·54	-	—
*d(28·5) Plain Expansion	28·5	471·57	0	471·6	—	—	—	1670·2	28·23	-	—
*d(29) Plain Expansion	29·1	495·6	0	495·6	—	—	—	1686·3	29·41	-	—

* Special case to accompany Figs. 4, 5, and 6, to show limiting conditions with reduction of pressure of interheating; this being now P+dP, where P=vacuum pressure.

of view, the " work area " would have been a rectangle, and in consideration of this problem I have found it of great use for every steam cycle to calculate what I have called the equivalent Carnot temperature and denote it by the symbols C (t). This Carnot temperature is that temperature which if a horizontal line be drawn parallel with the evaporation and condensation compression to the top temperature. The horizontal line would then be entirely an evaporation line and the vertical line an adiabatic expansion line to the original temperature in which the steam would all be condensed at the constant temperature of the vacuum.

This is a description of how steam would act were water a perfect fluid from the heat engine point of view

SCHEDULE 3.

Diagram Efficiencies obtainable from Steam Initially at 500 *lb. per sq. in. abs. pressure* 688° *F. Temperature with Two Interheats to* 688° *F. compared with Plain Expansion* (H_0=1355·9 *therms*).

Stage Pressure for First Interheat to 688 F.	Stage Pressure for Second Interheat to 688 F.	Final Expansion Pressure Vacuum (Barometer 30 in.)	Available Work to First Stage Pressure	Available Work First to Second Stage Pressure after Interheating	Available Work Second Stage to Final Presure after Interheating	Summation Available Work Three Stages	Heat to be Added for First Reheat to 688 F.	Heat to be Added for Second Reheat to 688° F.	Heat Added in Generation Less Heat in Feed	Summation Heat Less Heat in Feed	Thermodynamic Efficiency $\frac{W}{H}$	Equivalent Carnot Temperature, C (t)	Gain Due to Two Interheats over Plain Expansion
lb. per sq. in. abs.	lb. per sq. in. abs.	Hg. in.	therms	therms	therms	therms	therms	therms	therms	therms	per cent	° F.	per cent
365	150	28·0	36·9	98·4	394·1	529·4	44·2	109·9	1287·0	1441·1	36·76	426·9	3·5
365	150	28·5	36·9	98·4	409·6	544·9	44·2	109·9	1296·4	1450·5	37·56	423·2	3·3
365	150	29·1	36·9	98·4	435·9	571·2	44·2	109·9	1312·2	1466·3	38·95	417·4	3·1
365	100	28·0	36·9	136·9	370·8	544·6	44·2	151·1	1287·0	1482·3	36·74	426·7	3·5
365	100	28·5	36·9	136·9	386·6	560·4	44·2	151·1	1296·4	1491·7	37·57	423·5	3·3
365	100	29·1	36·9	136·9	413·7	587·5	44·2	151·1	1312·2	1507·5	38·97	417·8	3·2
365	70	28·0	36·9	167·9	349·8	554·6	44·2	183·7	1287·0	1514·9	36·61	424·9	3·1
365	70	28·5	36·9	167·9	366·0	570·8	44·2	183·7	1296·4	1524·3	37·45	421·6	3·0
365	70	29·1	36·9	167·9	393·7	598·5	44·2	183·7	1312·2	1540·1	38·88	416·6	3·0
280	100	28·0	66·2	112·9	370·8	549·9	78·1	122·5	1287·0	1487·6	36·98	430·2	4·2
280	100	28·5	66·2	112·9	386·6	565·7	78·1	122·5	1296·4	1497·0	37·79	426·5	3·9
280	100	29·1	66·2	112·9	413·7	592·8	78·1	122·5	1312·2	1512·8	39·18	420·8	3·8
215	70	28·0	93·3	122·6	349·8	565·7	108·7	130·3	1287·0	1526·0	37·08	441·4	4·4
215	70	28·5	93·3	122·6	366·0	581·9	108·7	130·3	1296·4	1535·4	37·89	426·0	4·2
215	70	29·1	93·3	122·6	393·7	609·6	108·7	130·3	1312·2	1551·2	39·30	422·4	4·1
150	50	28·0	127·2	121·0	329·6	577·8	146·0	126·4	1287·0	1559·4	37·05	441·0	4·3
150	50	28·5	127·2	121·0	346·2	594·4	146·0	126·4	1296·4	1568·8	37·88	428·0	4·2
150	50	29·1	127·2	121·0	374·5	622·7	146·0	126·4	1312·2	1584·6	39·37	423·5	4·2
150	45	28·0	127·2	131·0	322·9	581·1	146·0	136·7	1287·0	1569·7	37·03	440·6	4·2
150	45	28·5	127·2	131·0	339·7	597·9	146·0	136·7	1296·4	1579·1	37·87	427·8	4·1
150	45	29·1	127·2	131·0	368·1	626·3	146·0	136·7	1312·2	1594·1	39·32	422·6	4·1
150	40	—	127·2	142·0	316·1	585·3	146·0	147·9	1287·0	1580·9	37·01	440·4	4·2
150	40	–	127·2	142·0	333·0	602·2	146·0	147·9	1296·4	1590·3	37·87	427·8	4·1
150	40	—	127·2	142·0	361·6	630·8	146·0	147·9	1312·2	1606·1	39·27	422·0	4·0

lines and completed by the adiabatic expansion line, the condensation line and vertical line drawn from the start of the water line would give an area equal to the irregular work area already described. Such a rectangle expressed on the temperature-entropy ($T\phi$) diagram would be what would be obtained were the temperature of water to rise on being pumped into the boiler to the evaporation temperature, i.e. adiabatic and could therefore be worked strictly on the Carnot cycle.

Considering Fig. 1, it will be at once noticed that as so much heat has to be put into the feed water at a less temperature than the top temperature there is considerable loss of possible efficiency by the use of water as a working fluid. Without superheat, however, this loss, though considerable, is not very striking,

but when we come to consider the superheat part of the curve we see that the departure of the diagram from the plain rectangle is most marked. The additional superheat therefore makes the difference in efficiency between using a perfect fluid and using utilize this steam all provisions have to be made corresponding to the temperature of 688° F., the question of pressure very little entering into the practical provisions as drawn out by Mr. Shaw's paper. In fact the use of high pressure has already very much reduced this

SCHEDULE 4.

Diagram Efficiencies obtainable with Steam at Various Initial Pressures and Temperature 688° F. with One Interheat to 688° F. compared with Plain Expansion, to show Connection between Initial Pressure and Value of Interheating.

Initial Pressure	Stage Pressure for Interheat to 688° F.	Final Expansion Pressure Vacuum (Bar. 30 in.)	Available Work to Stage Pressure	Available Work to Final Pressure after Interheating	Summation Available Work	Heat added in Generation less Heat in Feed	Heat added to Reheat to 688° F.	Summation Heat less Heat in Feed	Thermodynamic Efficiency $\Sigma(W)/\Sigma(H)$	Equivalent Carnot Temperature, C (t)	Gain due to Interheat over Plain Expansion
lb. per sq. in. abs.	lb. per sq. in. abs.	Hg. in.	therms	therms	therms	therms	therms	therms	per cent	° F.	per cent
500	150	28·0	127·2	394·1	521·3	1287·0	146·0	1433·0	36·38	421·6	2·4
500	150	28·5	127·2	409·6	536·8	1296·4	146·0	1442·4	37·21	418·4	2·3
500	150	29·1	127·2	435·9	563·1	1312·2	146·0	1458·2	38·62	412·6	2·3
365	150	28·0	98·4	394·1	492·5	1294·3	109·9	1404·2	35·08	404·2	3·4
365	150	28·5	98·4	409·6	508·0	1303·7	109·9	1413·6	35·94	401·0	3·3
365	150	29·1	98·4	435·9	534·3	1319·5	109·9	1429·4	37·37	395·3	3·1
365	100	28·0	136·9	370·8	507·7	1294·3	151·1	1445·4	35·13	404·6	3·5
365	100	28·5	136·9	386·6	523·5	1303·7	151·1	1454·8	35·98	401·6	3·4
365	100	29·1	136·9	413·7	550·6	1319·5	151·1	1470·6	37·44	396·3	3·3
365	70	28·0	167·9	349·8	517·7	1294·3	183·7	1478·0	35·03	403·4	3·2
365	70	28·5	167·9	366·0	533·9	1303·7	183·7	1487·4	35·80	400·4	3·4
365	70	29·1	167·9	393·7	561·6	1319·5	183·7	1503·2	37·36	395·1	3·0
280	100	28·0	112·9	370·8	483·7	1298·9	122·5	1421·4	34·02	390·8	4·3
280	100	28·5	112·9	386·6	499·5	1308·3	122·5	1430·8	34·91	387·4	4·5
280	100	29·1	112·9	413·7	526·6	1324·1	122·5	1446·6	36·41	382·4	4·1
215	70	28·0	122·6	349·8	470·4	1302·4	130·3	1432·7	32·84	375·3	5·2
215	70	28·5	122·6	366·0	488·6	1311·8	130·3	1442·1	33·88	374·3	5·4
215	70	29·1	122·6	393·7	516·3	1327·6	130·3	1457·9	35·42	369·4	5·1
150	50	28·0	121·0	329·6	450·6	1305·8	126·4	1432·2	31·47	358·7	7·2
150	50	28·5	121·0	346·2	467·2	1315·2	126·4	1441·6	32·41	356·2	6·9
150	50	29·1	121·0	374·5	495·5	1331·0	126·4	1457·4	34·00	351·8	6·5
150	45	28·0	131·0	322·9	453·9	1305·8	136·7	1442·5	31·47	358·5	7·2
150	45	28·5	131·0	339·7	470·7	1315·2	136·7	1451·9	32·41	356·2	6·9
150	45	29·1	131·0	368·1	499·1	1331·0	136·7	1467·7	34·01	351·8	6·5
150	40	28·0	142·0	316·1	458·1	1305·8	147·9	1453·7	31·52	359·1	7·4
150	40	28·5	142·0	333·0	475·0	1315·2	147·9	1463·1	32·46	356·8	7·0
150	40	29·1	142·0	361·8	503·8	1331·0	147·9	1478·9	34·07	352·3	6·7

water very considerable. The actual figures are given in Schedule 7, and these show that for this first simple diagram at 500 lb. pressure without interheating and at a total temperature of 688° F., the use of the perfect fluid gives some 44 per cent higher efficiency than that of the plain use of steam. From the point of view of the materials used in the engine which is to difference which is far greater when the comparison is made with low-pressure steam, as can be seen by considering Schedule 5 which shows the value of pressure with a constant top temperature.

It will be gathered, as is well understood among engineers, that in order to approach the possible Carnot efficiencies it is necessary as much as possible to take

in all the heat at the top temperature, and for improvements in the use of water as a working fluid we can see from this temperature-entropy diagram that were it possible, so to speak, to keep our engine red hot, i.e. the equivalent of the Carnot hot body so that the temperature of the steam should not drop during expansion for a considerable time, then the engine which could do this would be working more nearly on the Carnot cycle because it would be taking in a further modicum of heat at the top temperature.

SCHEDULE 5.

Value of Pressure with Constant Top Temperature of 688° F. Pressure of 215 lb. abs. taken as Basis of Comparison.

Initial Pressure	Final Expansion Pressure Vacuum (Barometer 30 in.)	Available Work	Total Heat less Heat in Feed	Thermodynamic Efficiency	Equivalent Carnot Temperature, C (t)	Gain in Economy due to Pressure Basis 215 lb. Absolute
lb. per sq. in. abs.	Hg. in.	therms	therms	per cent	° F.	per cent
500	28·0	457·1	1287·0	35·51	409·8	11·6
500	28·5	471·57	1296·4	36·37	406·8	11·1
500	29·1	495·6	1312·2	37·76	400·6	10·2
365	28·0	441·9	1294·3	34·14	391·7	7·3
365	28·5	456·3	1303·7	35·01	388·6	7·0
365	29·1	480·9	1319·5	36·43	382·6	6·3
280	28·0	428·5	1298·9	32·98	377·0	3·6
280	28·5	443·2	1308·3	33·88	374·3	3·5
280	29·1	468·4	1324·1	35·38	369·1	3·2
215	28·0	414·2	1302·4	31·82	362·8	0
215	28·5	429·3	1311·8	32·73	359·8	0
215	29·1	455·0	1327·6	34·27	354·9	0
200	28·0	410·4	1303·1	31·50	358·9	— 1·0
200	28·5	425·5	1312·5	32·42	356·2	— 0·9
200	29·1	451·3	1328·3	33·98	351·6	— 0·8
150	28·0	394·1	1305·8	30·18	343·4	— 5·2
150	28·5	409·6	1315·2	31·15	341·1	— 4·8
150	29·1	435·9	1331·0	32·75	336·2	— 4·4
100	28·0	370·8	1308·5	28·34	322·7	—10·9
100	28·5	386·6	1317·9	29·34	320·6	—10·3
100	29·1	413·7	1333·7	31·01	316·5	— 9·5
90	28·0	364·6	1309·0	27·86	317·7	—12·5
90	28·5	380·6	1318·4	28·87	315·4	—11·8
90	29·1	407·7	1334·2	30·56	311·5	—10·8
80	28·0	357·7	1309·6	27·32	311·8	—14·1
80	28·5	373·8	1319·0	28·33	310·0	—13·4
80	29·1	401·3	1334·8	30·05	305·8	—12·3
70	28·0	349·8	1310·1	26·70	305·3	—16·1
70	28·5	366·0	1319·5	27·73	304·2	—15·3
70	29·1	393·7	1335·3	29·48	299·7	—14·0

SCHEDULE 6.

Value of Pressure with Constant Degree of Superheat of 219·3° F. Pressure of 215 lb. abs. taken as Basis of Comparison.

Initial Pressure	Final Expansion Pressure Vacuum (Barometer 30 in.)	Available Work	Total Heat less Heat in Feed	Thermodynamic Efficiency	Equivalent Carnot Temperature C. (t)	Gain in Economy due to Pressure Basis 215 lb. Absolute
lb. per sq. in. abs.	Hg. in.	therms	therms	per cent	° F.	per cent
500	28·0	457·1	1287·0	35·51	409·8	13·7
500	28·5	471·6	1296·4	36·37	406·8	13·1
500	29·1	495·6	1312·2	37·76	400·6	12·0
365	28·0	433·3	1276·9	33·93	389·0	8·6
365	28·5	447·6	1286·3	34·80	386·1	8·2
365	29·1	472·0	1302·1	36·24	380·3	7·5
280	28·0	413·4	1268·6	32·59	372·0	4·3
280	28·5	427·9	1278·0	33·41	368·3	3·9
280	29·1	452·6	1293·8	34·97	363·5	3·8
215	28·0	393·6	1260·5	31·23	355·7	0·0
215	28·5	408·3	1269·9	32·15	353·1	0·0
215	29·1	433·3	1285·7	33·70	348·0	0·0
200	28·0	388·2	1258·3	30·85	351·2	— 1·2
200	28·5	402·9	1267·7	31·79	348·5	— 1·1
200	29·1	428·1	1283·5	33·35	343·8	— 1·0
150	28·0	367·0	1249·8	29·36	334·2	— 6·0
150	28·5	381·9	1259·2	30·33	331·8	— 5·7
150	29·1	407·4	1275·0	31·93	327·0	— 5·2
100	28·0	337·0	1238·1	27·22	310·7	—12·8
100	28·5	352·3	1247·5	28·24	308·7	—12·2
100	29·1	378·4	1263·3	29·95	304·7	—11·2
90	28·0	329·3	1235·2	26·66	304·9	—14·6
90	28·5	344·7	1244·6	27·70	303·0	—13·8
90	29·1	370·9	1260·4	29·43	299·2	—12·7
80	28·0	320·8	1231·9	26·04	298·4	—16·6
80	28·5	336·2	1241·3	27·09	296·5	—15·7
80	29·1	362·5	1257·1	28·83	292·7	—14·4
70	28·0	311·0	1229·9	25·28	290·8	—19·1
70	28·5	326·6	1239·3	26·35	288·9	—18·0
70	29·1	353·1	1255·1	28·13	285·3	—16·5

In the Carnot cycle this heating during expansion or, as it is generally called, isothermal expansion, is carried on to a certain pressure and then stopped. This pressure is such that on further adiabatic expansion

the working fluid falls in temperature to the basis or lower temperature. To embody this concept it will be seen in Fig. 1 that there is a horizontal line drawn from the top temperature marked continuous interheating to such pressures (there stated) as will give steam just dry at the range of vacuum chosen to cover all ordinary cases. Supposing for a minute that such a system were physically possible, then we can easily judge the gain in efficiency due to what I have termed for the purpose of this diagram "Ideal Interheating." It is not ideal in the sense that the actual figures taken give the highest possible efficiency, but rather because It is not possible, however, to go further into this aspect of the matter, as such extension of the interheating scheme would give a different result for every initial pressure. We therefore get from this diagram certain figures which are embodied in Schedule 7 and show the maximum increase in efficiency to be expected from such a scheme as I have there termed "ideal interheating," this amount being about 11 per cent. A moment's reflection will suggest, however, that such a scheme of continuous interheating would be very difficult to carry out in practice, and in any case instead of the horizontal

SCHEDULE 7.

Summary of Comparative Efficiency.

	Thermodynamic Efficiency			Equivalent Carnot Temperature			Gain in Economy over Plain Expansion		
	(*a*)	(*b*)	(*c*)	(*a*)	(*b*)	(*c*)	(*a*)	(*b*)	(*c*)
	per cent	per cent	per cent	° F.	° F.	° F.	per cent	per cent	per cent
Use of a perfect fluid between temperature limits, t_0=688° F. and t_1=101·1° F. (28 in.), 91·7° F. (28·5 in.), 75·6° F. (29·1 in.).	51·12	51·95	53·37	688·0	688·0	688·0	44·0	42·9	41·4
Use of steam at 500 lb. abs. pressure superheated to 688° F. and maintained isothermally during expansion to pressures of (*a*) 21·88 lb. abs., (*b*) 17·66 lb. abs., (*c*) 12·03 lb. abs.; and then expanded adiabatically to (*a*) 28 in., (*b*) 28·5 in., (*c*) 29·1 in...	39·33	40·34	42·01	464·5	464·7	462·3	10·8	10·9	11·3
Use of steam at 500 lb. abs. pressure superheated, etc., expanded to 215 lb. reheated to 688° F., expanded to 70 lb., reheated to 688° F. and finally expanded to (*a*) 28 in., (*b*) 28·5 in., (*c*) 29·1 in.	37·08	37·89	39·30	441·4	426·0	422·4	4·4	4·2	4·1
Use of steam at 500 lb. abs. pressure superheated to 688° F. and expanded to 150 lb. abs., reheated to 688° F., and finally expanded to (*a*) 28 in., (*b*) 28·5 in., (*c*) 29·1 in.	36·38	37·21	38·62	421·6	418·4	412·6	2·4	2·3	2·3
Use of steam at 500 lb. abs. pressure superheated to 688° F. and expanded direct to (*a*) 28 in., (*b*) 28·5 in., (*c*) 29·1 in.	35·51	36·37	37·76	409·8	406·8	400·6	0	0	0

the further modicum of heat has been added exactly on the principle of the Carnot cycle and therefore at the highest possible efficiency as regards this added modicum alone.

I might just mention that the interheating could be carried to a still lower pressure with a still further gain in efficiency, because the main part of the diagram to the left of the interheating space is still large compared with the whole and therefore constitutes such a drag on the combined areas that an addition to the whole of a further portion of interheating area even at a lower efficiency than the ideal efficiency would still bring up slightly the overall efficiency of the cycle. continuous interheating line we should have the saw-toothed curve representing interheating at every expansion in the case of the turbine engine. The natural course of inquiry therefore turns as to what can be attained by doing something towards interheating in the simplest possible way. I do not propose to discuss at this time whether one single interheating would be best done by leading the steam back to the boilers or by having a gas-fired interheater close to the turbine and leading the exhaust gases back to the boilers, but one would naturally in turning to this inquiry remember that the higher the pressure of the interheat the more easy it would be to convey steam from and to the

engine. Taking as more or less accepted the possible use of 500 lb. steam as described in Mr. Shaw's paper, it will have been noticed that in the schedules various lower pressures have been selected as other standards with which to make comparisons. The next lowest pressure from 500 lb., viz. 365 lb., is practically that at which the plant is running at the British Thomson-Houston Company's works at Rugby, and I believe it is proposed to run one of the super-stations in this district at this pressure. The next lower pressure, viz. 280 lb., is at or about the pressure selected both for Glasgow and New Carville. The next lower pressure, 215 lb., is that at which many of our largest stations are running to-day, while many only a little smaller are running at 200 lb. abs. (185 lb. gauge).

There are also quite a number of old stations of which 150 lb. was the pressure for Lancashire boilers and which have installed watertube boilers at the same pressure. Pressures below these which have been taken have a direct connection with industry, in that at these pressure schemes are now in operation and many are proposed for bleeding off steam for industrial purposes. I have therefore included the effects of interheating at each of these selected pressures, the same being quite sufficient to explore the whole range of pressure. As before pointed out, there are two schemes on which one can elect to do interheating, the first and more correct is to the initial temperature and the second or less correct is to the same initial superheat. It is almost obvious that one would not reheat to higher than the original temperature. Somewhere between these two schemes therefore any practical scheme must lie.

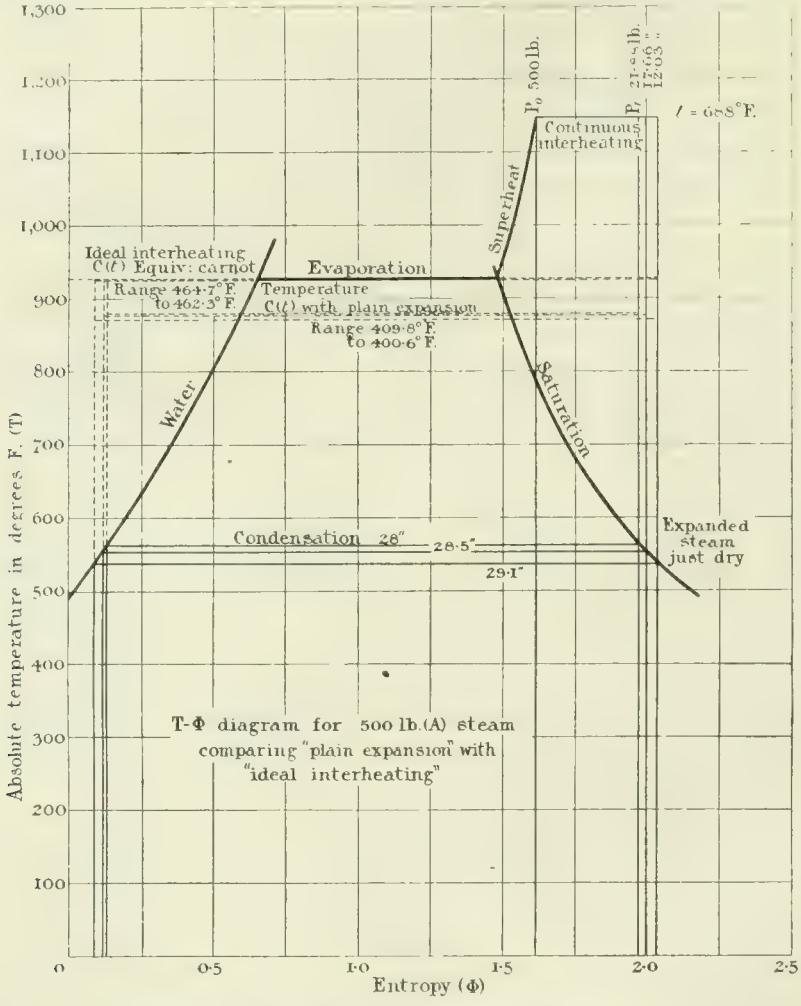


FIG. 1.—Temperature-Entropy diagram for 500 lb. (abs.) steam, comparing "plain expansion" with "ideal interheating."

In Fig. 2 I have outlined a scheme for single interheating at stage pressures of 365 lb. and 280 lb. Such selection does not at once commend itself, but it is very useful to see the effect of selecting these pressures which are clearly shown on this figure. It will be seen that the added area due to interheating is small compared with the area to the left, and therefore we could not expect much practical gain at these pressures.

In Fig. 3 I have drawn out a single interheat for stage pressures of 215 and 100 lb., and in this case it will be seen that the added area is a substantial

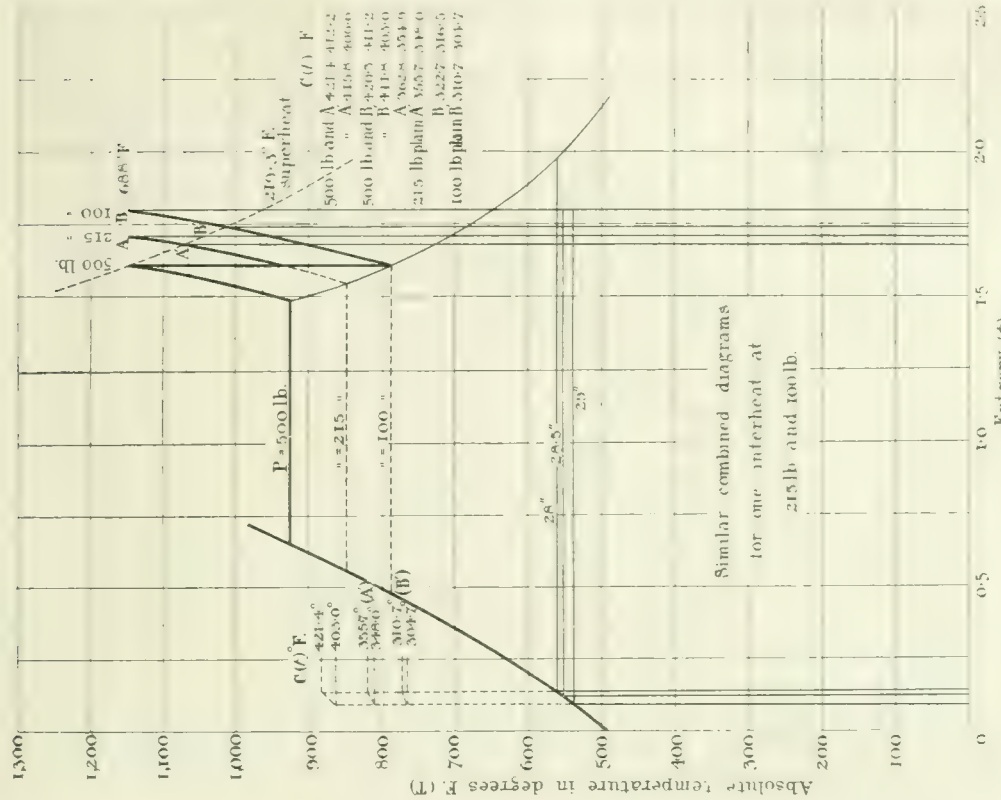


FIG. 3.—Similar combined diagrams for one interheat at 215 lb. and 100 lb.

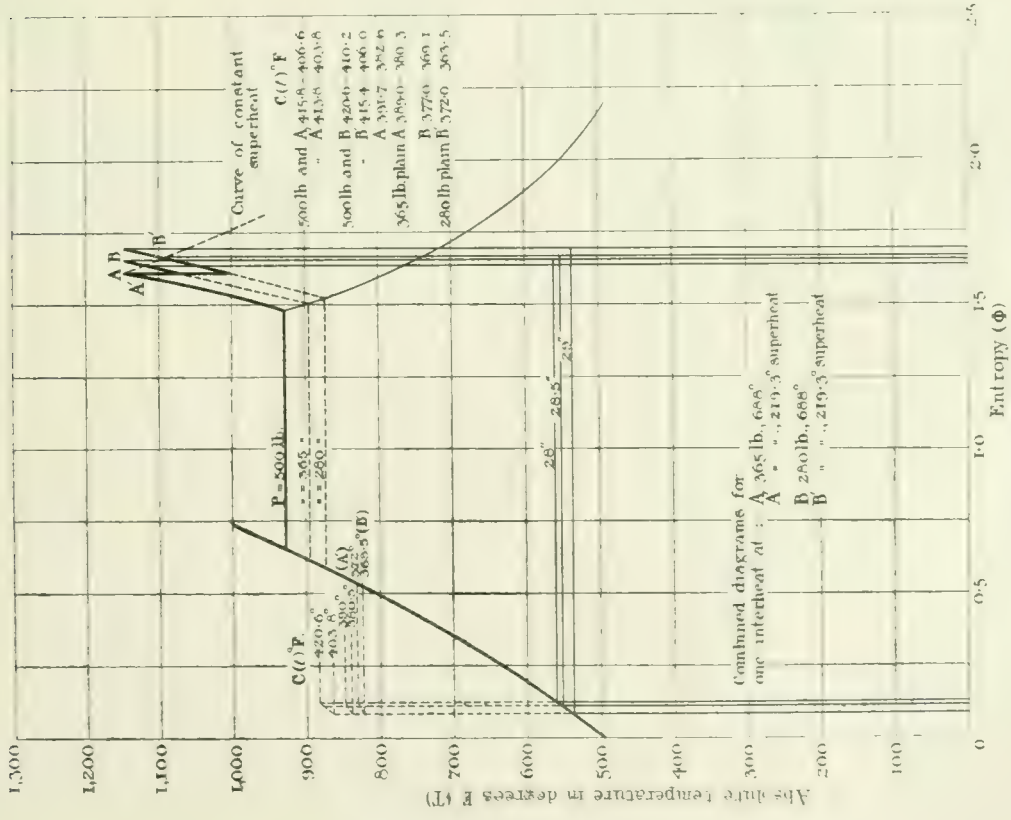


FIG. 2.—Combined diagrams for one interheat at :—

A 365 lb., 688° F. B 280 lb., 688° F.
A' 365 lb. 219·3 degrees F. superheat. B' 280 lb., 219·3 degrees F. superheat.

portion of the "ideal interheating" area shown in Fig. 1.

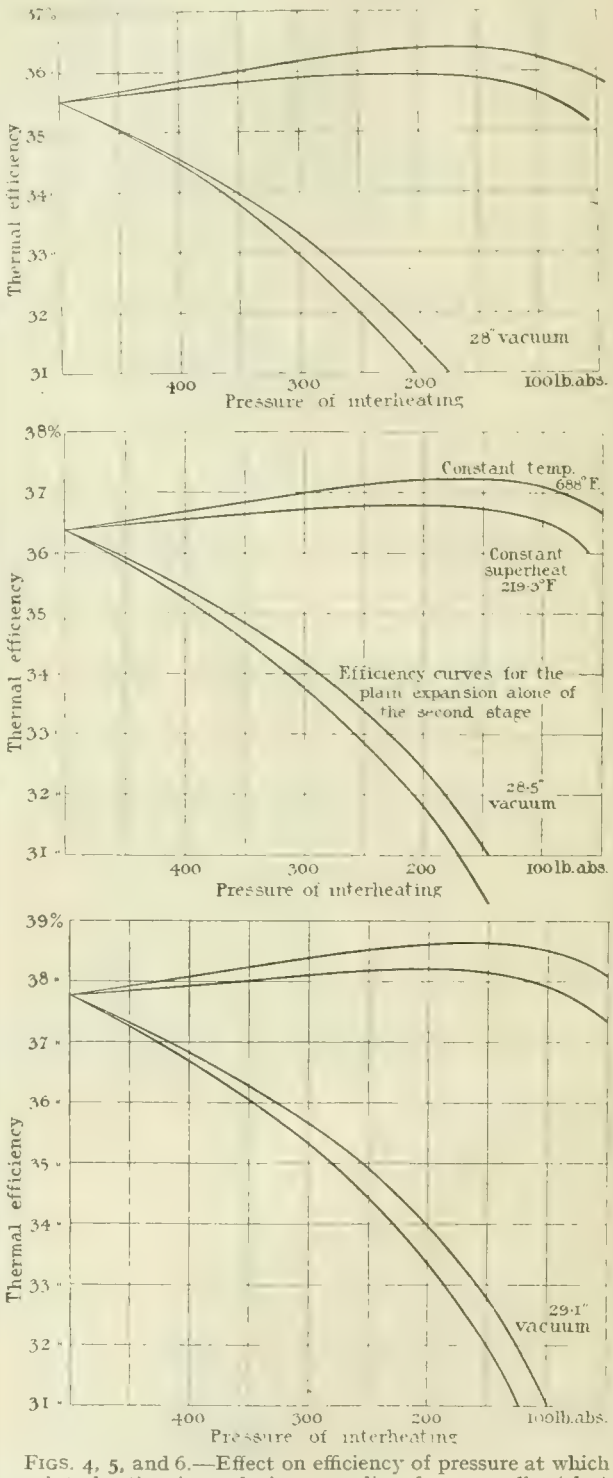
Schedule 1 also shows that somewhere between these two pressures will be found the maximum gain which will be made with one interheating.

These figures are quite sufficient to show the nature of a problem, and so in Figs. 4, 5, and 6 I have combined the whole of these results in curves which show the effect of one interheat at any pressure below the initial pressure. It is necessary to draw three different curves for each vacuum. In addition to the efficiency curves for the combined expansion with one interheat I have also drawn the efficiency curves for the second expansion alone. Figs. 4 to 6 therefore give not only the value of interheating but a direct comparison of the efficiencies between different pressures. The way in which the efficiency rises with pressure as compared with interheat strongly illustrates what has already been mentioned as to the value of pressure. In considering Fig. 3 we notice that the single saw-tooth gives us a curve which is very far from representing heat fully taken in at the top temperature, and it is therefore interesting to extend the inquiry into the region of more than one interheat, and here I think one would have to abandon the idea altogether of taking the steam back to the boiler but not entirely that of bringing the heat to the engine.

In Fig. 7 I have drawn out the superheat region of the temperature-entropy diagram to a larger scale and have given the superheat portion of the curve from the saturation line up to the constant top temperature of 688° F. for all the pressures given in the schedules. It is very easy from this diagram therefore to take as many saw-teeth as are likely to be of interest. It is only proposed, however, to consider a few of these as given in Schedule 3. The lines which have been drawn in slightly heavier than the others show three sets of conditions. For the first expansion these are to stages of 280 lb., 215 lb., and 150 lb. respectively. In the first case re-expansion after 280 lb. is naturally to about 100 lb. In the second case re-expansion after 215 lb. is naturally to 70 lb. In the third case re-expansion after 150 lb. is naturally to about 50—40 lb.

In exploring this diagram we can now see the advantage of drawing what I have called the "Carnot zone," which is a narrow horizontal band covering the range of the "Carnot temperatures" for the range to a vacuum of from 28 to 29·1 inches. Bearing in mind that our object is to take in as much heat as possible at the top temperature, and considering that we have already explored the efficiency for plain expansion and for one interheat, it is obvious that in dropping down any vertical line of adiabatic expansion for any stage of expansion we cannot hope to gain much in efficiency after we have got down to the Carnot zone. Without this diagram it would have been extremely difficult to have decided what to explore in the way of more than one interheat or what pressure to consider. A mathematical investigation as to what would be the best pressures would have been very cumbersome.

Turning to the results as shown in Schedule 3, we note that the curve of the whole range of efficiency obtained from two interheats would be exceedingly flat, and this shows us that it would not be necessary



FIGS. 4, 5, and 6.—Effect on efficiency of pressure at which one interheating is made in expanding from 500 lb. (abs.) to vacuum.

to define any particular set of exact pressures. Also, once given the high initial pressure of 500 lb., the actual efficiencies do not show much encouragement.

We have only gained about 4·4 per cent over plain expansion and therefore only 2 per cent over a gain of a single interheat. This is to say that the second interheat does not show quite so great an increase as the first interheat, and this rather discourages us from proceeding any further into the region of three or more interheats, as we already have the figure of 11 per cent for ideal interheating as shown in Fig. 1. Nevertheless, it would be quite easy to make a quick calculation from Fig. 7 because the superheat curves are so straight that it would be quite easy to take any intercept between various adiabatic lines as a straight line and from this make a quick calculation as to the efficiency of the added portion, the efficiency of the original plain expansion being fully determined in the view, making a maximum use of the existing plant, and this is likely to be a matter for some consideration in view of the high prices for plant which are likely to prevail for very long periods.

It is hoped that this short communication will round off the question of the possibilities of efficiency in the use of high-pressure and high-temperature steam so ably dealt with by Mr. Shaw.

Inquirers into the future will have probably turned their thoughts in two directions. One will be the use of a working fluid which has a greater ratio of latent heat to specific heat than in the case of steam.

Referring to Fig. 1, this would mean that the water line to the left would rise much more sharply. Such a working fluid is mercury which has a latent heat of

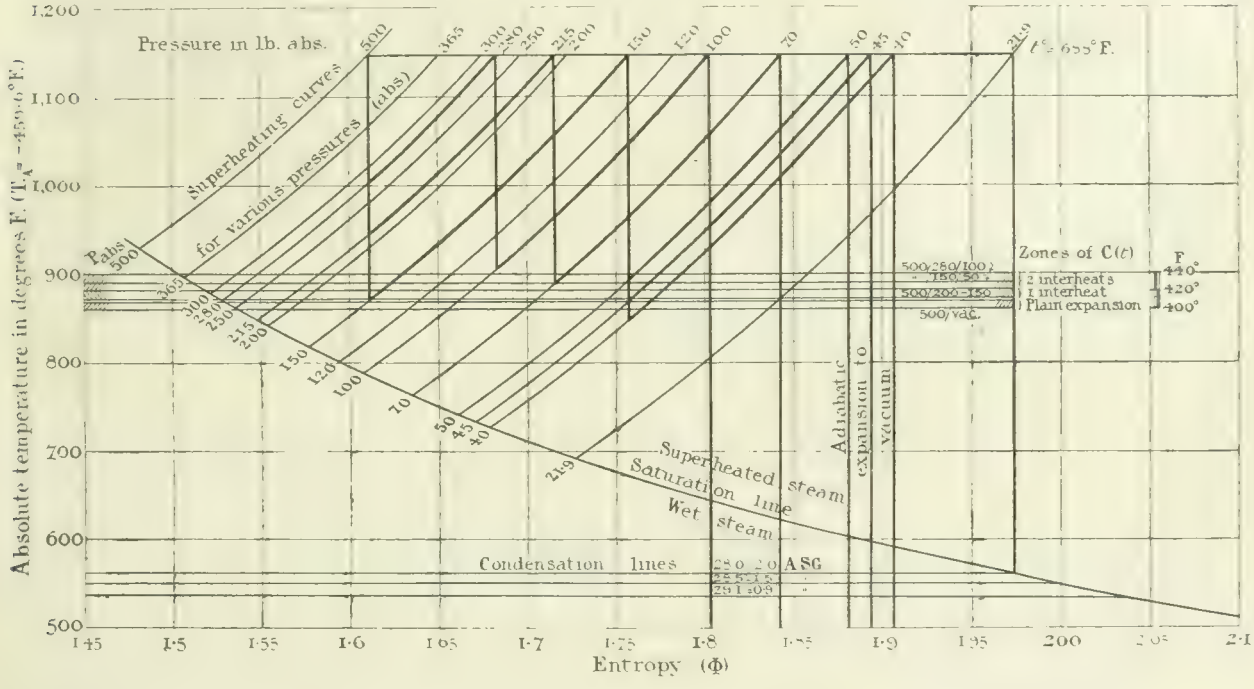


FIG. 7.—Temperature-Entropy diagram for 500 lb. (abs.). Right-hand portion enlarged to show effect of more than one interheat (see Figs. 1–3) to a constant top temperature of 688° F.

schedules. One further reflection arises on Schedule 4, and that is that the gain due to one interheat is very much greater at moderate pressures than at the highest pressures. This rather signifies that the scheme may be of some value to old stations which have perfectly good plant only suitable for moderate steam pressure. There is nothing to prevent such steam being fed into any type of engine arranged for interheating, provided the heat is brought to the turbine instead of the steam from the engine being taken back to the boilers. Under this arrangement it would not be necessary to modify the boiler plant at all, but it would mean the addition of a producer gas plant to the power station which is a very likely development in the future. Moreover, it would not be very difficult to modify many existing turbines to take interheated steam so that the scheme might be worth going into from a practical point of

68 calories and a specific heat of 0·033. Another direction in which the working fluid could be modified is that its evaporation line should be at a high temperature for a given pressure, provided always that condensation can easily be obtained at a moderately low temperature. In this direction again mercury perhaps offers advantages, since its temperature of evaporation at ordinary atmospheric pressure is about 358° C. while its vapour pressure even at a temperature of boiling water is exceedingly small. The other direction which inquiries will take is probably that of a double-fluid engine. This is a scheme of interheating but with change of fluid whereby the rejected heat of the first fluid is at such a temperature as to be able to evaporate the second fluid.

This again is really a case of endeavouring to make the "work area" of Fig. 1 more nearly approach the shape of a rectangle. The idea is of course very

old and has been explored by using reciprocating engines with steam together with sulphur-dioxide as a second fluid. Other vapours at low boiling points have been suggested. Quite recently, too, all engineers have been much interested in the account given of the Still engine which proposes a double working fluid, first air and then steam. This is of course quite old, but the method by which it is applied has apparently given quite good success.

As regards the air part of the cycle, of course quite good efficiencies are already obtained in the plain gas engine, and gas engine designers have often considered the question and have generally come to the conclusion that the gain in power by adding the steam cycle did not justify the extra complication of the engine, especially as they have been able to find many ready uses for the exhaust heat in process work.

With regard to the efficiencies now obtainable with plain gas engines, I would recommend every electrical engineer to read carefully Dugald Clerk's book on the Gas, Petrol, and Oil Engine. Quite apart from whether he may be interested in the course of his business in such a question, it is most enlightening to read classics written by great workers in other lines, and its perusal will probably give him considerable pleasure.

It is very interesting to compare these steam cycle efficiencies with the data given on the sheet of curves relating to gas engine efficiencies in the Gas, Petrol, and Oil Engine, by Dugald Clerk (1910, vol. 1, p. 310). I do not here reproduce this diagram but it will be sufficient to quote the following approximate figures :—

	Efficiencies with Compression Ratio of		
	5	6	7
Air standard $= 1-(1/r)^{\gamma-1}$ ..	48·2	51·0	54·8
Ideal efficiency actual working fluid	38·5	41·5	43·9
Diagram efficiencies obtained, i.e. 88 per cent of ideal obtainable with actual working fluid	33·8	36·4	38·7

We see from this diagram (without going into the arguments and experiments by which it is obtained) that the efficiency obtainable from the actual working fluid compared with that obtainable from an ideal working fluid is in the ratio of 0·71 to 0·88, that is about 80·6 per cent. This is a much greater difference than perhaps is usually appreciated by steam engineers. If we compare the case of ideal interheating at 500 lb. with the ideal Carnot efficiencies based on the temperature range we see that the corresponding ratio is of the order of 78 per cent, which is remarkably similar. Even in the case of plain expansion this ratio is about 70 per cent. Another curious coincidence can be traced in the fact that the explosion pressures are of the order of 450—470 lb., which is very close to the 500 lb. absolute adopted for the purpose of these calculations. Another coincidence is that, taking into account the value of superheat and its effect on turbine efficiency, a modern turbine of largest size will have an efficiency ratio at the coupling of 85 per cent, which again is remarkably close to the mechanical efficiency of a large gas engine. We may conclude therefore that in the near future the steam turbine may equal if not surpass the gas engine in efficiency, the competition being still more severe in overall efficiency since the efficiency of large boilers in the most modern practice is now showing a margin of nearly 10 per cent over the corresponding gas producer efficiency. The battle, if any, which may range between these two methods of producing power in the future may turn on the direct total utilization of their rejected heat, which is still unfortunately, under any system, of the order of 60 to 70 per cent. It is along these lines one look for progress rather than in much further improvement of the efficiency of these prime movers, and there are already signs that a very vigorous interest is being taken by engineering economists in questions arising out of the utilization of the rejected heat of both forms of working fluid.

APPENDIX 2.

All the figures and data which have been used and prepared in these schedules are taken from the figures contained in the Steam Tables by Professor Callender published by Arnold (1915 edition). The explanation given in connection with these tables is so full as hardly to need any comment. Wherever possible in preparing the schedules the figures for available work have been taken from the Heat Drop Tables (absolute pressures) by Messrs. Moss and Callender published by Arnold in 1917. The calculation for continuous interheating is very simple, since having already calculated the plain expansion the added heat is simply $T\,d\phi$ and the gain in available work $(T_0-T_1)\,d\phi$. Heat drops not available from the tables have been calculated from the formula at the foot of page 24, Table 2, of Callender's tables, which is quite easy to manage. One little point is perhaps worth mentioning, viz. that in calculating available work during a stage expansion in which the steam is fully superheated the simplest plan is to take the steam as an ordinary perfect gas with $\gamma=1{\cdot}3$ and calculate a temperature at the end of the expansion. Having then found both initial and final pressures and temperatures it is easy to take out the total heat, and its change must be the available work.

In preparing the schedules I have used the range of vacuum from 28 to 29·1 inches, as this method of describing vacuum seems to be impossible to alter. What these figures mean of course are absolute pressures of 2·0 inches down to 0·9 inch of mercury.

SCOTTISH CENTRE: CHAIRMAN'S ADDRESS

By W. B. Hird, Member.

(*Address delivered at* Glasgow, 11 *November*, 1919.)

In choosing a subject for my address this evening, I was naturally drawn to consider the many inventions and developments which took place during the war, and which, necessarily kept secret during the continuation of hostilities, are now only just getting generally known and open to discussion. In all the different branches of engineering, of physics, of chemistry, and of military science, new strides were taken with a rapidity which only the great stress and necessity of the times could have brought about, a rapidity utterly impossible in times of peace when every new thing must show at any rate some prospect of commercial success before it can hope to receive encouragement.

The particular feature to which I would specially draw attention is the marked tendency towards an increasingly close connection between pure science and its applications in engineering and practical work generally. The time is not far distant, but it has gone for ever, when the work done in the physical laboratory and in the study of the mathematician was looked on askance by the man who boasted of being "practical."

Perhaps one of the most striking instances of this closer connection between theory and practice is the very large use which has been made of the apparatus known as the thermionic valve. For some years the attention of some of our best physicists has been directed to investigations of the electron, but it was scarcely to be expected that investigations which were started and carried on solely from the point of view of pure science and which were directed to such highly abstract considerations as the constitution of the atom of matter and the changes which might take place in its constitution would, in so short a time, have developed into an instrument of great practical utility, which could be manufactured in quantities by comparatively unskilled labour and required no great amount of training in those who used it to give useful results.

The study of the electron has been going on for a comparatively short number of years. Many apparently unconnected observations had previously been made of phenomena which had not received a full explanation. For instance, it had long been known that the air in the neighbourhood of red-hot metals was electrified. In 1884, experiments carried out on an incandescent lamp showed what was then known as the "Edison effect." A separate electrode was sealed into the glass of an incandescent lamp so as to reach between the two legs of the horse-shoe filament. When this filament was made incandescent a galvanometer connected between the negative end of the filament and the electrode showed practically no deflection, but when it was connected between the electrode and the positive end of the filament, a current was observed flowing in the direction from the filament to the plate.

The discovery was also made of rays which had the property of affecting photographic plates and which were capable of passing in varying degree through substances opaque to light vibrations; the very name which still survives of "X" rays shows what an unknown quantity they appeared to the first investigators.

The first attempts at any connected explanation of these and similar phenomena became possible when in 1890 Sir J. J. Thomson published the results of his investigations and introduced to science the conception of "electrons" or, as they were originally called, "corpuscles," masses infinitely smaller than the mass of the hydrogen atom, which up to that time had been conceived the smallest unit in existence, and each carrying a definite charge of negative electricity.

The study of the electron has gone on since that date. It has occupied the most eminent men in physics and mathematics, and we may well be filled with amazement at the results obtained in the comparatively few years that have elapsed, and at the wonderful amount of information we now possess as to the properties and behaviour of this minute and elusive constituent of the atom.

It has been found possible to count accurately the number of free electrons in a conductor carrying a current, or in a given space in an exhausted bulb. Not only has the number of free electrons been counted, but it has been found that they are all of equal mass and all carry or are associated with a given definite quantity of electricity, and this mass and quantity have been accurately measured.

The investigations and experiments carried out have been largely directed to increasing our knowledge of the ultimate constitution of matter. It is now presumed that the atom consists of a number of electrons kept in equilibrium by the attraction of a positively charged nucleus, and several different mathematical models of the atom have been discussed. The chemist has brought his particular knowledge to bear on the question, and the probability of any particular hypothetical arrangement of electrons in the atom will be largely judged by whether it gives a satisfactory explanation of the periodic law of the chemist. According to this law a list of the elements arranged in the order of their atomic weights can be tabulated so as to fall into groups having similar chemical properties. The atom will contain an increasing number of electrons as the atomic weight increases, and the present endeavour is to formulate such a law for the arrangement of these electrons as will cause the model atoms also to fall into

groups with the same periodic recurrence of similar configurations.

It is one of the most prominent signs of the accelerating effect of the abnormal conditions we have gone through, that investigations directed primarily to considerations of such an abstract subject should have so rapidly and quickly developed into so concrete a result as the production of thermionic valves, which were manufactured during the war in hundreds of thousands and were used in huge numbers for varied purposes.

The theory of the electron and the results of experiments show that electrons are given off from the atoms of which they form a constituent part under a variety of circumstances, but in order that they may be detected they must be caused to move in a definite direction in a continuous stream. This stream of electrons has the properties of an electric current, it can be deflected by a magnet or can itself deflect a compass needle, the path of the stream can be made visible by placing parallel to the lines of flow a piece of mica coated with a fluorescent substance. The electrons impinging on this cause the material to fluoresce and thus trace their path on the mica plate. It is only possible to obtain this flow of electrons in a highly exhausted bulb. If any air or other gas at anything like atmospheric pressure is present, the path of the free electrons becomes very much shortened on account of their collisions with the particles of gas, and moreover they "ionize" the gas. The effect of the collisions is to cause the gas particle to part with some of the electrons of which it is built up, and the remaining nucleus thus carries an excess of positive charge, the presence of which obscures the action of the electrons. The first condition, then, is to operate in a highly exhausted space.

The second necessary condition is that there should be an electric force present in this vacuum to give the electrons a definite direction of motion.

The actual emission of electrons into the vacuum may be obtained in different ways. If a sufficiently high difference of potential is employed between the two electrodes, the electric force will be sufficient itself to determine the throwing off of electrons from the cathode.

This is the method used in tubes for the production of X rays. The two electrodes sealed into the exhausted glass bulb are connected to the terminals of the secondary winding of a coil capable of giving in air a spark of several inches. The high voltage thus applied to the electrodes causes a stream of electrons to flow from cathode to anode and, if the degree of exhaustion is appropriate, gives rise to the cathode rays, which in their turn in impinging on the glass of the bulb cause the radiation of X rays.

An incandescent metal or carbon filament will throw off electrons, and in this case a very moderate electric force is sufficient to give these a definite direction. In some of the thermionic valves in use, the electromotive force between the filament and the plate is only about 30 volts.

Another case of the spontaneous emission of atoms is seen in the case of radium and other so-called "radioactive" elements, the atoms of which spontaneously break up, some of the products of this decomposition being electrons.

The method of the hot filament is that used in the production of thermionic valves.

An incandescent cathode contained in a highly exhausted vessel gives out these negatively charged corpuscles. These being free to move in any direction will, if not under the influence of any directing force, show no signs of motion in any particular direction. The greater part of those that escape from the surface of the metal will in time return and be re-absorbed in the body itself. If, however, an electric force is present in the space in which these electrons are emitted, it will act on the free electrons and give them a definite direction.

If, for instance, a negatively charged body is brought near the incandescent filament, the electrons will be repelled and will return to the filament, but if a positively charged body is substituted, the electrons will be attracted and there will be a definite flow from the filament to the electrode.

In its simplest form and consisting merely of a filament and an electrode, the valve has been used as a rectifier. It is evident from what has already been said, that if a source of alternating potential is connected to the filament and the electrode, a stream of electrons will pass during those periods of time when the electrode is positively charged with respect to the filament. In the alternate intervals when the electrode is negative, the electrons are repelled into the filament and no action takes place, thus the valve—and hence is its name derived—will let through current in one direction but refuses passage in the other.

A further development is the introduction of a third electrode. This electrode usually consists of a spiral wire or thin plate pierced with holes, and is placed between the filament and the anode, the whole of these being contained in a highly exhausted vessel. The addition of this third electrode, generally called the grid, transforms the valve from being merely a rectifying device into a kind of relay which can give a large amplification to any oscillations it receives. When a thermionic current is passing between the filament and the anode, any change in the potential of the grid will, by attracting or repelling electrons, change their rate of flow between filament and anode and therefore alter the value of the thermionic current.

A comparatively small difference of potential between the filament and the grid will cause a very much greater difference of potential between the filament and the anode, and in this way the valve can be used as an amplifier and quite small differences of potential impressed between the filament and the grid will be magnified and appear as much greater differences between the filament and the plate.

This property of amplifying any oscillating electromotive force applied to the grid circuit can be made use of to generate alternating current. The plate circuit of the valve is connected to one coil of a transformer, the second coil of which is connected to the grid, any small oscillating potential difference being applied to the grid circuit; a magnified oscillation will result in the plate circuit, and this through the action

of the two transformer coils will react upon and increase the oscillation in the grid circuit. The circuits will thus "build up" in the same sort of way as a direct-current generator starting with a small amount of permanent magnetism gradually "builds up" until a state of equilibrium is reached. In the same way an "ionic" valve, connected as above described, will increase the amplitude of the vibrations until the whole system steadies to a state of equilibrium.

The frequency of the oscillation depends on the ratio of inductance to capacity in the plate circuit, and by varying these values it can be changed within very wide limits. Experiments described by Mr. W. C. White in the *General Electric Review* showed that the valve used could be made to give oscillations varying from one-half period up to 50 million periods per second. The current obtained by these means is not only very steady and for many purposes very useful on account of the large range of periodicity to which it can be readily adjusted, but is also of a very pure sine-wave form.

From this short description of the thermionic valve it will be seen that whether it is used as a rectifier, as a relay for amplifying received impulses, or as a generator of oscillating current, the principle is in all cases the same, a stream of electrons flowing from filament to plate is acted upon by the charged grid.

Compare this with the rectifiers, relays and converters which were the best at our disposal before the discovery of the electron, and it is easily seen how vastly superior is an instrument which instead of having to rely on influencing material moving parts of a more or less clumsy construction deals with electrons of a mass only a little greater than one 2,000th part of that of an hydrogen atom. It is necessary to look at it in this way in order to realize the possibility of the results actually obtained in practice.

The applications of thermionic valves have so far been chiefly in the service of wireless telegraphy, and of the newer branch wireless telephony.

In the British Navy, Army and Air Forces, the progress made in wireless communications was largely due to the introduction of thermionic valves both as amplifiers in the receiver and as generators of high-frequency oscillations in the transmitter.

In 1914 and 1915, three electrode valves were used for wireless transmitters in a more or less experimental way in the Navy, and from that time the use of these instruments became more and more standardized. The improvements effected were rather in the details of construction than in principle, and consisted in obtaining a higher degree of vacuum in the bulb and in discovering the best materials to use for the different electrodes.

As early as 1915 communication was made between H.M.S. *Vernon* in Portsmouth and a ship off the Northumberland coast, the current in the aerial of the *Vernon* being only 0·6 ampere. In 1916, with further improved transmitting valves using 2,000 volts in the plate circuit, a current of 8 to 10 amperes was obtained in the aerial of the *Vernon* and communication was got with Gibraltar. In 1918, sets were being supplied to the Grand Fleet as rapidly as they could be manufactured.

In the Air Force, the wonderful improvement in intercommunication made chiefly by the use of the ionic valves is strikingly realized when we learn that, of the aircraft originally sent over to France with the Expeditionary Force, one only was fitted with wireless apparatus, while at the signing of the armistice about 500 machines were so fitted and there were 2,000 wireless stations with the batteries capable of communicating with these machines.

The original sets in use in aeroplanes were in some cases worked from batteries, others from engine-driven sets, and had a capacity of 50 to 150 watts. They varied in weight from about 1 lb. to $\frac{1}{2}$ lb. per watt output. It was not till 1916 that receiving as well as transmitting apparatus was regularly fitted to aeroplanes, and this was effected by the use of thermionic valves as amplifiers. At the same time, valves were used experimentally for the purpose of transmitting and receiving wireless telephone messages.

It is obvious that if a system of waves interrupted by the use of a Morse key will transmit Morse signals, it is only a question of finding a detector sufficiently delicate and prompt in response in order to enable us to receive the signals caused by the interruption and variation of these wave trains by the vibration of a telephone diaphragm. The variations caused by these sound vibrations are so rapid and of such slight values that no very great success was obtained until ionic valves used as amplifiers were used as receivers. A valve will amplify the oscillations received on the grid circuit differently, according to the construction of the valve and to the potential differences at which it is used. The valves so far obtained vary from an increase of about 5 times to 30 times, but any number of such valves can be connected as it were in series, the oscillation in the plate circuit of No. 1 being impressed on the grid circuit of No. 2, another magnification being thus obtained, and the process can be repeated as often as desired.

The Americans have developed the use of this instrument for wireless telephony to a greater extent, and experiments have been carried out when telephonic communication was obtained between New York and San Francisco, New York and Honolulu, and finally between New York and Paris. In some of these experiments as many as 300 three-electrode valves were used; and if it be assumed that each valve magnified 5 times, the magnification obtained by 300 in series would be of the order of 5 to the power of 300.

One very striking use of such magnification has been the detection of ordinary telephonic conversations at the Front. By driving metallic rods into the ground at a distance of a few hundred yards apart, the line joining them being roughly parallel to the enemy telephonic lines, it was possible to tap the return earth current. When the extremely small value of the current in an ordinary telephone line is considered, and how extremely attenuated the earth current must be at a lateral distance from the line which must be considerable, since it must include at least the distance between the front line trenches, the fact that it was found possible to intercept conversations going on

behind the German lines is an excellent testimonial to the magnifying power of the valves used.

I have laid particular stress on the evolution and practical application of the thermionic valve, because it is the most marked example of the connection between the work of the scientist and of the practical engineer, but many other examples of a close connection between the laboratory and the workshop are to be found.

The rapid progress made in the science of aviation has resulted from the action and reaction of practical experience and theoretical investigations. At the beginning of the war our knowledge of the laws of pressure on bodies moving through a fluid was of a very elementary character. It is true that the equations of motion of a fluid about an object of any given shape are old and well known, but their solution has not hitherto been found possible for practical purposes except in a few simple cases and when the motion is steady and free from eddies. It is, I believe, still the fact that no solution of the flow of air round any of the bodies used in aviation has been calculated from the equations of motion, and that all our knowledge of stream lines in such cases is due to experiment, but it is nevertheless true that our knowledge has been very greatly increased, if indeed it cannot be said to be entirely due to the mathematician and the physicist.

One of the most useful steps was the publication by Lord Rayleigh of the formula for the variation in the air pressure due to change of dimensions of the moving body, and it is entirely due to the application of the law thus formulated that experiments in aviation were kept on sound lines and that the results have proved the astounding success which we have seen.

Without this guide, not only would it have been impossible to work with small models to scale, the number of possible experiments being thus hugely reduced, but the actual results obtained during the flights of full-sized machines would have been chaotic and applied only with great uncertainty and difficulty to evolving either improved efficiency or increased size.

Another totally different direction in which we can see science coming into closer contact with practical work is in connection with the methods of shop organization now being so widely discussed. The up-to-date shop organizer is no longer satisfied merely to observe for himself the effect of fatigue, to time and tabulate the different motions gone through in carrying out any operation, but he calls in the assistance of the physiologist and the psychologist to devise laboratory experiments and to draw on his experience in quite different spheres to advise him as to the proper proportion of work and rest periods, to discuss the different results of nerve and muscle fatigue, and the mental attitude produced in different groups of workers by changes in their environment.

Nay, even the mathematician steps in, and it has recently been proposed to apply the mathematical law of probability to discover whether or not there is any deliberate attempt to restrict output, the principle being that on dividing a number of workers performing the same operation into groups according to their ability as indicated by their output, counting the numbers in each group and plotting the results as a graph, the curve should be symmetrical about its average value if the observations have been carried out on a sufficiently large number. If, however, any extraneous cause, such as a deliberate attempt of the more able to hide their ability in order to restrict output, is introduced, the symmetry of the curve about its mean value will vanish.

Other examples of the results of scientific research during the war are the improvement in range finders, the finding of range and direction of an enemy gun through the agency of the sound waves produced by its discharge; the use of a reflected sound wave, an echo in fact of a sound produced at the observation post, to detect the presence of unseen objects whether in the air or under water; the production of the hydrophone, a telephone receiver capable of being submerged and which being kept rotating indicates the direction of the impending sound waves by giving the loudest indication at the moment when the plane of the diaphragm comes into coincidence with the wave front. These are all examples of the direct use made of scientific methods and of the services of scientific men. Nor would I have it thought that this is by any means a complete catalogue of what has been done in this way; rather is it a short list of a few samples taken almost at random from a very large number.

If, turning from the past, we venture to glance at the future, we can scarcely hope—perhaps we ought not to hope—that the rapidity of adaptation of scientific discovery to practical work developed in quite abnormal times will continue under more normal conditions. We may not unreasonably hope, however, that the closer connection and the more rapid adaptation of scientific discoveries will to a large extent be maintained under the new conditions we are all looking forward to, and it is gratifying to note that among the many projected reforms and reorganizations the setting up of research laboratories by large industrial concerns, and the stimulating of an increased public interest in scientific work, are not forgotten.

It is also gratifying to find that an increased interest is being taken in societies such as our own Institution, which are the most powerful link between the scientist and the engineer, and that we are all increasing our membership, striving to add to our spheres of activity and to organize and fit ourselves for the work before us.

Great as has been the work of the engineer in the past century in bringing into our services first steam and then electricity, if we consider the centuries that elapsed between Hero's first steam-driven model and the evolution of the modern steam turbine, if we remember that electricity was known to the ancient Greeks and that barely a few years have elapsed since any practical use was made of it, and if we compare these periods with the history of the electron unknown yesterday, to-day usefully employed for our benefit, it may well seem that we may be on the brink of a new era the possibilities of which are as yet undreamed of.

For if each fresh discovery opens up ever vaster fields of inquiry, it is also true that a larger and larger number of workers mentally equipped to carry out the exploration are each year available, and it is part of

our work as an Institution to see that the supply of such workers is kept up to the requisite standard and that their work and efforts are properly appreciated.

It is only necessary to glance at any technical or scientific journal to see how large a proportion of the time and attention of present-day science is engaged in problems of radio-activity and of the constitution of the atom; and however imperfect our knowledge, however much we still have to learn as to the properties of the electron and how it enters into that combination which we call the atom, there is one point on which there cannot be considered to be any doubt, and that is the immense quantity of energy stored up in the atom of matter. It has been calculated that the average energy stored up in one grain of radium is sufficient to raise 100,000 tons of water from freezing to boiling-point, and atoms of other elements contain energy in quantities of the same order of magnitude. At present this energy is entirely out of our control, the atom breaks up spontaneously, and we have no means of either retarding or accelerating the process, nor have we as yet any means of using it. Perhaps we never shall find means of bringing it under control, but the knowledge that such an inexhaustible store of energy is available makes it possible to hope, without too great a stretch of the imagination, that some means of using it will some day be forthcoming, and we may then anticipate such a revolution in the conditions of living as will absolutely throw into the shade the changes of the last 100 years brought about by the discovery of the steam engine and the electric telegraph. For we are all convinced that improved methods of obtaining and distributing power are the one important factor in obtaining better conditions of life. To the engineer the fact is patent, and even writers describing modern social utopias all find it necessary to postulate large developments—in their case vague and obscure development—in the methods of obtaining and distributing energy in order to be able to attain to their standard of ideal existence. Already in the ionic valve we are making some practical use of atomic energy. In wireless telegraphy we are transmitting not inconsiderable quantities of energy to great distances without material connection, and surely if further developments do follow whether in the immediate or the distant future, they will be so intimately connected with the work of the electrical engineer that he will perforce take a leading part in bringing them about.

If any excuse is required for drawing members' attention to possibilities which at present are rather in the realm of romance than of actuality, it is only necessary to point to the changes and forecasts of changes in every department of activity around us. Our military leaders during the war were often accused of a lack of imagination to which many failures were attributed. It may be that occasionally to indulge our imagination may also help in times of peace.

NORTH-WESTERN CENTRE: CHAIRMAN'S ADDRESS

By J. A. Robertson, Member.

(*Address delivered at* Manchester, 18 *November*, 1919.)

For the first time for six years we meet under actual peace conditions.

The bitter struggle in which this nation with her Allies entered upon in 1914, with its terrible toll of life, human suffering, and material destruction, has ended in a complete, let us hope a final victory for all our Allies. We remember at this time those members of this Centre who went out to do their duty in the early days of the war. A number of these have made the great sacrifice, others have returned mentally and physically disabled. We pay to-night our tribute to the memories of those who have fallen. To those who have returned let us see that at any rate they are reinstated in civil life, and that they will not be at a disadvantage on account of the sacrifices they have made.

The part played by the electrical industry in the war is being recorded officially by the Ministry of Munitions, and the first portion of the published returns dealing with power supply during the war reveals some striking results.

When called on to provide an adequate supply of power for the manufacture of munitions, power stations were labouring under serious disadvantages in 1915. In the early days of the war, and before its real nature had been grasped, power station staffs were depleted owing to technical assistants and skilled men leaving for naval or military service. When, later, the country became organized for war munitions output, large and urgent demands for power were made. Existing plant had to be run to its full capacity, including all reserve or stand-by plant, new plant had to be hurriedly installed and risks taken which would not have been justified under any other than war conditions. Working under the disadvantages of depleted staffs, shortage of labour, scarcity and low quality of fuel supplies, and with ordinary maintenance work postponed indefinitely, the power stations were able nevertheless to meet all demands made by the Ministry and thereby to assist in the manufacture of munitions, which at that time were of vital national necessity and could not have been turned out had a public supply of power not been available.

One result of the increased electrical activity during the war was to stimulate its employment for ordinary industrial purposes, and to place electricity beyond all doubt as the most efficient, reliable and cheapest form of power for all industrial and manufacturing purposes.

Between August 1914 and November 1918 the supply of electricity from public generating stations had been doubled, and the plant installed, or ordered during the war, was greater in capacity than all the plant in use in August 1914. Most of this plant was supplied on the "rationed" principle, and it must be said that on the whole the Ministry of Munitions, who had the responsibility for issuing permits to enable plant to be purchased, carried out their duties with fairness and discretion.

It was not surprising that the increased use of electricity called attention to the possibility of cheap power production, and the question of centralization under joint control became a problem of vital national importance.

The advantages of centralized production of electricity on a large scale and its distribution over wide areas were of course well known before the war. The difficulties in carrying out any scheme of unification were political rather than commercial or technical. The Board of Trade since 1883 had granted Provisional Orders to companies and local authorities on the assumption that the local authority area, already delimited for administrative purposes, was also a suitable area for the supply of electricity. The Electric Lighting Act of 1883 undoubtedly favoured municipal control, and placed restrictions on private enterprise which at that stage tended to retard progress.

Something may, however, be said for the Board of Trade. Public utilities, such as water, gas, and tramways, had in previous years been entrusted to private companies, and the results were not encouraging. The Board apparently determined that this new public utility, then used for lighting purposes only, and likely to be a strong competitor of the gas industry, should be placed under public control.

The Electric Lighting Act of 1888 was rather more favourable to private enterprise, chiefly by increasing the period of concession from 21 to 42 years, and providing that at the end of that period the undertaking might be purchased at its "then" value. It does not, however, appear to have stimulated private enterprise to any great extent, and many of the company undertakings which were set up in the eighties were purchased from the companies by the local authorities under agreement long before the period of tenure had expired.

The power companies who obtained supply rights in perpetuity over large areas between 1898 and 1902 had not up to 1914 made much progress in the direction of cheap power production, and in only a few cases had local authorities closed down their small stations in favour of bulk supplies. How far this was due to local jealousies and how far due to the inability of the power companies to furnish cheap supplies need not be discussed here; the fact remains that it required

the strain of this great war to bring the importance of cheap electricity supply into the region of national politics.

The first actual step in this direction was really taken by the reading of Mr. E. T. Williams's paper * before the Institution in the early part of 1916. This paper put forward bold comprehensive proposals for national electricity supply under a Board of Commissioners in London. The scheme included the erection of super-stations, transmission lines, and supplies in bulk to local authorities over districts to be set up by the Commissioners.

At a discussion on the paper in Manchester in April 1916, I ventured to state that Mr. Williams's proposals were impracticable under the conditions at that time, when the problem was really one of immediate and abundant supplies of power for all purposes. As an alternative I suggested the linking up of existing stations as a means of increasing the output from the present plant and affording reliability of supply.

As an outcome of the discussion a committee of engineers was appointed about two weeks later to report on a linking-up scheme for Lancashire and Cheshire. It should be explained here why that scheme fell through. In preparing their second Report, which was intended to formulate a detailed linking-up scheme, the Committee felt that to make linking up effective, a full measure of central control was necessary. The hours of running of each station must be controlled by a central authority, and it followed that the central authority must also decide at what stations extensions of plant should be carried out. The erection of new stations by the central board followed as a matter of course.

The majority of the Committee felt that the Report, to be of any value, must put forward a full scheme which would provide not only for linking up, but also for the joint ownership and control of generating stations. The second Report was considered at a conference representing 35 supply authorities in December 1917, and by a majority of two to one (each authority having equal voting power) the local authorities refused to consider the latter portion of the engineers' scheme dealing with the purchase of existing stations and the erection of new stations.

The decision was, I think, unfortunate. Had it been otherwise, Lancashire would have had the opportunity of setting an example to the rest of the country by carrying out proposals which were, in all essentials, identical with the main proposals in the Electricity Bill now before Parliament.

But the work of the linking-up Committee was not altogether fruitless. It brought the question prominently before local authorities and engineers, and linking-up Committees became the fashion throughout the country. A number of instances of voluntary linking up have taken place, some of them in Lancashire. Perhaps the most interesting of these is the recent linking up of Manchester and Salford. Here we have a case where the political conditions could hardly be described as favourable. The two authorities have not hitherto shown an overwhelming desire for co-operation in public utility work, but in this instance the proposal was adopted unanimously by both Corporations.

A cable has been laid of 10,000 kw. capacity at 33,000 volts between the Moss Side substation of Manchester Corporation and the Salford generating station in Frederick-road. The energy is stepped up from 6,600 to 33,000 volts at Moss Side, and stepped down again at Frederick-road to 6,600 volts, where the two systems are operated in parallel.

In the meantime provision is made for a supply of 5,000 kw. by Manchester to Salford, but this can be increased to the full capacity of the cable by installing a second set of transformers.

It may be mentioned that the Salford system, in addition to operating in parallel with Manchester, also operates in parallel with the system of the Lancashire Power Company. The Power Company's system is connected to two generating stations each generating at 6,600 volts, so that we have a series of five linked-up stations extending from Manchester in the east to Wigan in the west.

Following the Reports of the Lancashire Committee, the Special Committee on Power Supply appointed by the Board of Trade issued its Report in June of last year, and as a result we have the Electricity (Supply) Bill which is now before Parliament.

This Bill, which has now emerged from the Committee stage in Parliament, is by far the most important event in the history of electricity supply in this country, and is bound to exercise an enormous influence on future developments.

The report of the proceedings in Committee shows that the proposals in the Bill have undergone the most exhaustive and searching scrutiny. Company and municipal interests have been ably represented, and while compromises have naturally had to be effected, the Bill will, I think, be accepted in its present form by the supply industry at large as being on the whole a comprehensive and satisfactory measure for dealing with what is now an extremely complicated problem.

The most striking feature of the Bill is the enormous powers which are to be exercised by the five Commissioners to be appointed "to promote, regulate, and supervise" the supply of electricity. They are to create areas for purposes of electricity supply, to constitute District Boards, to approve, modify, or reject schemes formulated by local authorities or others, to bring forward schemes themselves, to lend money, to control prices, and to fix such minor matters as the type of current, frequency, and pressure employed for the new systems. They are also to be allowed to spend 20 million pounds on new schemes within two years after the passing of the Bill. They will, in short, exercise complete control over the whole electricity supply industry. Such powers are quite unprecedented, and their exercise will call for men of undoubted standing and ability who can be trusted to act impartially and who are free from any interest political, commerical, or otherwise, which might clash with their duties as Commissioners. So far the only Commissioner appointed is the Chairman, and it will be a source of satisfaction to power station engineers that the choice has fallen upon Sir John Snell, a Past-President of this Institution, who is not only an engineer of great ability and wide experience, but who possesses to an

* *Journal I.E.E.*, 1916, vol. 54, p. 581.

exceptional degree the confidence of all parties—municipal and company—interested in electricity supply.

The discussion of the Bill has largely centred round Clauses 5 and 7, and some material alterations have been made to both. On Clause 5, which originally proposed to confer powers on the Commissioners to create electricity districts and constitute District Electricity Boards who were to be responsible for a "cheap and abundant supply of electricity" within the district, with powers to acquire existing generating stations and transmission lines, and to construct new generating stations, an important compromise has been made. Instead of setting up District Boards in each of the districts, the Commissioners now may exercise any one of three alternatives. If they are satisfied with the existing organization for electricity supply, they may leave matters as they are; or if they are not satisfied, they may hold an inquiry at which any local authority or other interested party may put forward a scheme for consideration, which the Commissioners may accept, or modify, or reject. If the scheme is accepted, a joint electricity authority may be formed under the scheme comprising the various undertakers within the district, with or without the addition of large consumers and other interests. This Board will have power to take over existing undertakings in whole or in part, and exercise the provisions of the Act which apply to District Electricity Boards.

The third alternative is that if the Commissioners are not satisfied with the existing organization, and if the authorities or those interested cannot or will not themselves put forward a scheme, i.e. if the authorities do not co-operate on a scheme which receives the approval of the Electricity Commissioners, the Commissioners may then set up a District Board which will carry out a scheme, including the taking over of power stations and the erection of new stations with or without the consent of the supply authorities.

The effect of the modification is to make the provisions more elastic, and to give the local authorities and companies themselves a chance to co-operate on a combined scheme.

The terms on which existing stations and transmission lines may be purchased as set forth in Clause 7 have, as expected, given rise to acute controversy, the criticism coming with equal force and measure from municipal and company representatives respectively. The "standard price" in the case of local authority stations may either be the outstanding capital liabilities in respect of the station, payable in the form of annuities for interest and sinking fund charges, or, as amended, the local authority is entitled, if it desires, to have the price determined by an arbitrator on the basis of capital cost of the station, less depreciation. An increased amount is also to be paid on account of any portion of the station or transmission lines which has been paid for from Revenue Account. In the case of companies the "standard price" is to be the certified cost of the generating station and transmission lines, less an amount for depreciation, to be determined by the Electricity Commissioners, and plus an allowance for "loss by severance."

The critics of the purchase terms in the case of local authorities contend that owing to the operation of sinking funds and the increase of values, the generating stations of local authorities are worth considerably more than the standard price, under either of the alternatives offered. It will be found that, as a rule, local authority generating stations have redeemed on the average not less than 40 and in many cases as much as 60 per cent of the original capital expenditure, and as the value of plant has increased from 2 to $2\frac{1}{2}$ times over pre-war prices, the Joint Boards or District Boards will make a very good bargain indeed.

Another criticism is that the terms make no distinction between the prudent and imprudent local authorities. The authority which has not only been redeeming its capital by way of sinking fund but has depreciated in addition, is to receive no recognition over the authority which has only made provision in the past for statutory sinking-fund requirements, transferring all surplus profits for the benefit of the district rates.

There is much force in this criticism, but it must be remembered that local authorities are not, strictly speaking, trading for profit. Their proper function as a public authority is to ensure that a cheap and efficient supply of electricity is available for the community they represent. The changes proposed in the Bill simply mean the transfer of their responsibilities and liabilities to the new authority, and they will reap the benefit of cheap purchase of their stations by the District Board in the reduced rates charged to them for bulk supplies.

In the case of companies the conditions are somewhat different. They have invested their shareholders' money in providing electricity supply under parliamentary sanction with the perfectly natural object of making a profit from the business.

Whether the ownership of public utilities by private companies under limited tenures is a right policy or not need not be discussed now. The fact is that these companies were willing to risk their capital in providing public supplies of electricity at a time when the local authorities themselves were not prepared to do so. They have been operating under parliamentary guarantees regarding purchase terms, and it would be contrary to all our parliamentary and national traditions to take their generating stations from them now on terms less favourable than they are entitled to under existing Acts of Parliament.

The terms were discussed at considerable length in Committee, and it is unfortunate that a compromise satisfactory to the companies could not be arrived at. The matter will probably be raised again in Parliament. The Government are evidently prepared to recognize that the companies are entitled to better terms, because in a later clause—Clause 12—it is provided that if the company's generating station is taken over by a District Board, the company may, within two years, call on the District Board to take over their distribution system also at the original capital cost of the whole undertaking, less the sum already received for the generating station. The effect is, of course, that if the companies lose their generating stations, and wish, as many of them will, also to dispose of their distribution systems, they will receive the original value of the whole

undertaking, including the station, without any deduction for depreciation.

The provisions of Clauses 7 and 12 as they stand appear to be designed to drive private companies out of the business of electricity supply, and I trust that Clause 7 may be so amended that the Companies will receive the same terms for the station alone as it is proposed under Clause 12 for the whole undertaking.

There is one provision in Clause 7 which is, I think, open to very grave objection. Sub-section 5 stipulates that when a generating station has been taken over by a District Board, the Board is obliged to supply the authority from whom it is taken with electricity not less in amount than could have been generated at the transferred station and at a price not greater than that at which it could have been generated, having regard to any reduction of costs which may have been expected to accrue from improvements contemplated on the 8th May, 1919.

This provision simply bristles with difficulties and will give rise to interminable disputes. Who is to decide what the station could have generated at if certain contemplated improvements had been carried out? This is a task too big even for the Commissioners. The chief objection, however, in my opinion, is one of principle. The provision strikes a blow at the main purpose for which this Bill has been drafted. The anomaly at the present time in nearly all industrial districts is the difference in prices and rates charged by the various supply authorities. A consumer situated in one area may be charged a certain rate for electrical energy, say to a cotton mill. Half a mile away a consumer requiring an exactly similar supply, operating under the same circumstances as regards load factor and cost of transmission, may be charged rates 50 per cent more because the energy is furnished by another supply authority. Surely we had a right to expect that anomalies would be swept away by the Electricity Bill, and that the new authority, Joint Board or District Board, set up for that district would be in the same position as regards equality of rates and "no preference" in furnishing supplies as the existing authorities who are debarred from showing preference to one consumer over another taking the supply "under similar circumstances."

Under Sub-Section 5 the anomaly is to be continued in perpetuity. The various supply authorities will be entitled and obliged to receive bulk supplies from the District Board at prices based on the previous costs of generation. If the generation costs at one station were high, the prices charged by the District Board will be high, although the cost of transmission may actually be less than in other cases where the authorities are entitled to a cheaper supply because they were previously for some reason or another able to generate more cheaply than their neighbours. If such a provision has been introduced as a safeguard, it is entirely illusory, because the District Board is only bound to supply the amount which could have been generated at each station, and if a further amount is required, there is apparently no limit to the price which may be charged. This Sub-Section in my opinion is a most serious defect in the Bill. I trust it will yet be deleted, and that the District Boards will be obliged to supply energy to the distributing authorities over the whole of the respective electricity districts at uniform rates.

Under Clause 16 of the Bill, which authorizes District Electricity Boards with the sanction of the Electricity Commissioners to exercise their powers through authorized undertakers or by companies formed for the purpose, the Committee have by a large majority limited the District Board to exercising their powers through "authorized undertakers" only. The principle of public control has therefore been established in cases where schemes are financed with public money.

In Clause 17 the compensation terms for deprivation of employment have been enlarged, and will now, I think, be accepted as generally satisfactory by those interested.

Under Clause 15 the Board of Trade can authorize any District Board to abstract water from rivers or canals, and this power has now been extended in Committee to include all authorized undertakers. This is an important extension, and will be appreciated by those undertakers who have found it impossible to obtain condensing rights except at prohibitive prices.

The powers conferred by the Bill on various undertakers with regard to wayleaves for overhead wires and cables will remove a restriction hitherto exercisable by local authorities and land proprietors, which has long hampered electricity supply, especially in rural districts.

The power to hire (but not to sell) electrical apparatus is now extended to all local authorities, and an important proviso has been added that the fittings and appliances provided on consumers' premises either before or after the passing of the Act are to be held to form part of the undertaking.

It is gratifying to note that in addition to their administrative powers, the Commissioners will have power to make experiments with the object of improving the supply of electricity. There will be no question amongst engineers as to the necessity and urgency of such work. I am not overlooking what has been done by manufacturers in their laboratories or the research work carried on in many universities and colleges. In the case of manufacturers the drawback is that unless a new method or device is patentable, the manufacturer will hesitate to disclose the result of his investigations for the benefit of his competitors in trade. In this respect manufacturers may be very often short-sighted, and as they are now pooling their commercial resources, I suggest that with proper understanding and good faith they might be able to carry out co-operative research work for the benefit of the whole industry.

There is still much investigation required regarding the properties of insulating materials for high-pressure cables and generating plant, the corrosion of turbine blading, protective devices for high-tension systems, switchgear to deal with pressures up to 50,000 volts, and many similar problems. It is likely that within the next five years a sum of not less than 100 millions will be expended in the construction of new stations

and transmission lines, and a small fraction of this amount, say ¼ per cent, expended immediately on research work would prove a thoroughly sound investment.

It appears certain that within a very short time the Bill will become law and the supply authorities will be faced with some interesting and vital problems.

When the Commissioners come to create Electricity Districts, it will be found, I think, that in not more than one or two industrial areas matters will be allowed to remain as they are. Certain other districts, with stations situated far apart, where the power demand is not a pressing problem, may also be left alone in the meantime, but in the remaining districts—Lancashire, Yorkshire, the north and south Midlands, South Wales and London—Joint or District Boards are certain to be formed.

It appears likely that the Lancashire and Cheshire area will be one of the first to be dealt with, probably under three Boards, representing South-East Lancashire and a part of Cheshire, North Lancashire, and South-West Lancashire, the latter including the stations on the Wirral Peninsula in Cheshire.

The supply authorities in these districts will, in the first instance, have the opportunity of formulating schemes of their own for submission to the Electricity Commissioners.

Under such schemes the Board may be composed of authorized undertakers only, and it appears that in most cases such a Board will be preferable to a District Board which will have outside representatives, representing labour and large consumers.

The question is, will the local authorities be able to sink local jealousies and co-operate with each other and with companies for the purpose of a joint scheme?

The engineers, who are the responsible advisers of their Committees or Boards, have a tremendous responsibility, and their attitude will largely determine whether a voluntary scheme is adopted or not.

It is to be hoped that on this occasion, and having in view the fact that if they fail to agree on a voluntary scheme a District Board will be set up in which they will be compelled to take part, they may take a broad view, uninfluenced by personal or local considerations.

The technical problem will turn in most cases on the merits of local generating stations situated near the centre of their respective loads, as compared with supplies from one large station on a site suitable for economical generation but distant by comparison from the loads.

The advantages of the super-station are:—

(1) A favourable site for condensing, and for coal supplies and disposal of ashes, with ample room for extension.

(2) The lower capital cost per kilowatt of plant installed, higher load factor, lower costs for fuel, labour and maintenance.

Against these undoubted advantages, we have to set the cost of transmission—including capital charges on mains and the lower efficiency due to transformer and line losses.

It is a fact, I believe, that at the present time engineers are more divided amongst themselves as to the policy to be followed than they were a few years ago.

It is contended that the increased cost of super-station construction, which has risen fron £7 or £8 per kilowatt of plant installed to £20 or £22, with a corresponding increase in the cost of transmission lines, has turned the scale in favour of local generation.

On the other hand it is true that coal and labour costs have increased in almost the same proportion, but it is claimed that the saving from super-station generation in these items does not neutralize the increased capital charges on super-station construction.

It is impossible of course to apply any general rule to individual cases, and the factors vary so much that any estimate on general lines is apt to be misleading.

I do not propose to go into details, but will deal with one or two general points which should be taken into consideration when schemes come to be considered.

It may be admitted at once that in the case of a local station equipped with fairly modern plant at the prices obtaining prior to 1917, with natural condensing facilities sufficient to deal with the present load, and able to operate economically sets of 3,000 or 5,000 kw. capacity, it is extremely difficult to make out a case for supply from a super-station, say 8 or 10 miles distant.

There are a number of such stations in the Lancashire area which can show working costs that compare favourably with many of the larger stations now in operation. On commercial grounds there appears to be no good reason for closing down these stations at present in favour of a bulk supply.

In preparing a scheme for a whole district, the question must, however, be looked at from a broader point of view, regard being had not to present conditions, but to the conditions which may exist 7 to 10 years hence.

The main fact is that we are faced in these industrial districts with very much greater demands for electricity than we have been accustomed to in the past. All the evidence goes to show that the enormous increases during the war will be more than maintained, and it is the general experience that in the change-over from war conditions—which naturally meant a slowing down—we have already regained the position of November 1918, and that further demands are constantly being made.

It is not too much to estimate that within the next five years the present output will be at least doubled, and if the national scheme fulfils expectations, still greater increases may be looked for.

We have to consider then whether those local stations on restricted sites, with limited condensing facilities, will be able to meet all future demands for electricity in their areas, because if the continuance of the stations involves new expenditure on plant, the relative advantage of pre-war prices disappears. The erection of a new station, other than a super-station, in the industrial areas is unthinkable unless under most exceptional conditions.

Take the case of a district with a group of 10 or 12 local stations of varying capacity. One or two stations may be showing comparatively good results. The others

may not. There is nothing more remarkable than the variation in efficiency in stations situated in the same district and apparently operating under similar conditions as regards fuel prices and load. In a census taken by the Lancashire and Cheshire Interconnection Committee, the fuel consumption varied from 2·2 lb. to 8·5 lb. per unit.

In the case of the group referred to, it is probable that in three-fourths of the stations a bulk supply from a super-station favourably situated would show an advantage, while in the other two or three stations a case could be made out for local generation. If, however, a new super-station is required for the district, it may be good policy to close down the two or three efficient stations in addition to the 8 or 9 inefficient stations, to increase the load factor on the super-station, and so improve the supply to the whole district. The two or three efficient stations in the group would be interconnected and could be retained for stand-by or peak-load purposes up to the limit of their economical capacity.

After all, the supply of electricity cannot be considered by itself alone. It is essentially bound up with questions of transport, housing, industrial reconstruction, and the conservation of fuel.

The electrification of railways, which has been held up during the war, is certain to develop enormously in the near future. The work done by the Lancashire and Yorkshire Railway Company and by the London, Brighton and South Coast Railway Company has, I believe, given the greatest satisfaction, and new schemes in different parts of the country are being announced.

From the point of view of the travelling public there is no question as to the greater convenience and comfort of all electrified railways.

Under the new conditions, it is hardly likely that the mistake of constructing separate generating stations for railway supplies will be repeated. The load factor of railway supplies must be combined with the load factor of industrial supplies to get the best results. Under these conditions the fuel-saving by railway electrification has been estimated at 50 to 60 per cent. It is of the greatest importance that the two supplies should be combined, and the question of centralized generation versus local stations may in many cases be determined by this factor alone.

Another question that cannot be overlooked is the tendency for cities and towns to spread out in order to find improved housing accommodation for the workers. The industrial conditions of last century, when lack of transport led to the concentration of large populations in the industrial areas, is not likely to be perpetuated in the future.

As the towns spread out, many industries will follow. There is even now a tendency to remove some classes of factories from the city to the urban or district areas.

My point is that the tendency will be for the demand to spread out over a larger area, and the advantage of the local station to-day through its proximity to the load may be a diminishing factor in the future.

There remains the still greater and, I believe, the deciding factor of fuel conservation. A cheap and abundant supply of power—which is the object of the Electricity (Supply) Bill—cannot be considered apart from this question. The industrial life of this country depends for its existence on, and is limited in duration by, our supplies of coal. At the present rate of consumption our supplies of coal are estimated to last for 500 years, but as the more accessible and richer seams are worked out, a considerable increase in cost must take place long before that period has expired.

In passing, reference must be made to the repeated claims made by the gas authorities on behalf of coal carbonization as a means to effect fuel economy. One eminent authority a few years ago referred to the "barbarous methods" of consuming coal in boiler furnaces, and another authority (Lord Moulton) said the other day that "he hoped the Fuel Conservation Committee would not look to electricity as the solution of the difficulty of conserving our fuel resources, but would feel that the use of gas was the most potent weapon at their command," and still another authority (Sir Arthur Duckman) has said that "they should not have had Electricity Commissioners, they should have had Commissioners for heat, light, and power, tackling electricity and gas works, coke oven generation, and waste heat from blast furnaces. There should be no false competition between gas and electricity. They ought to run together."

On this question of coal carbonization, power station engineers have, I believe, an open mind. The urgent and primary need is for a supply of cheap power, and if this object can be more economically achieved by a process of carbonization, it will be welcomed by the electricity supply industry.

It may be admitted that the gas engine as a prime mover has a slightly higher efficiency than the steam boiler and turbine, but it is, of course, quite unsuited to power production on a large scale, while the distribution of gas over a large area for power purposes is not a practical proposition.

The combination of coal carbonization with the production of power is a question on which further information is urgently required. The Fuel Research Committee has been considering the matter for some years, but up to the present we are without any practical proposition which would justify the combination of coal carbonization and power production on a large scale for immediate requirements.

So far as we know, the production of gas for firing boilers presents no advantage in thermal efficiency, apart from the production of by-products, the chief of these being ammonia sulphate.

Over and over again experiments have been made which appeared to show favourable results, but there the matter ended.

The powers of the Electricity Commissioners (as extended in Committee) will enable them to conduct experiments on the utilization of fuel, and it is probable that some of the new stations to be erected will employ to a limited extent carbonization plant, with the object of gaining information and experience. In the meantime it appears certain that under the new power schemes, the great bulk of power production will be obtained from stations with coal-fired boilers and turbine-driven generators, showing a boiler-house efficiency of 80 to

85 per cent, and an overall thermal efficiency of 18 to 20 per cent.

The question is, what amount of fuel saving is possible by transferring the generation of electricity from a number of small and medium sized stations to a few large stations on favourable sites laid out to secure the highest possible efficiency?

Some useful information is available from the Coal Mines Department who have summarized the monthly returns of power-station fuel consumptions in the United Kingdom for the years 1918 and 1919. These returns ought to receive the serious attention of all interested in electricity supply and fuel conservation.

The summary includes returns from 438 electricity undertakings having an output of 4,745,000,000 units, and a total fuel consumption of 7,356,000 tons, including 31,000 tons of coke.

The stations are grouped in four classes, viz.

(*a*) Stations having an output of over 50 million units per annum;
(*b*) Stations having an output of between 15 million and 50 million units per annum;
(*c*) Stations having an output of between 3 million and 15 million units per annum, and
(*d*) Stations having an output under 3 million units per annum.

The average fuel consumption of all the stations was 3·47 lb. per unit generated for the year ended March 1919.

In group (*a*) the lowest fuel consumption of any station was 1·8 lb. per unit, representing a thermal efficiency of 18 per cent, the average being 2·76 lb. per unit, and the highest for any station 3·95 lb. per unit.

In group (*b*) the lowest fuel consumption of any station was 2·19 lb. per unit, representing a thermal efficiency of 14 per cent, the average being 3·39 lb. per unit, and the highest 6·75 lb. per unit.

In group (*c*) the lowest fuel consumption of any station was 2·61 lb. per unit, representing a thermal efficiency of 11·2 per cent, the average being 4·34 lb. per unit, and the highest 11·47 lb. per unit.

In group (*d*), the small stations, the lowest fuel consumption was 3·72 lb. per unit, representing a thermal efficiency of 7·2 per cent, the average being 6·95 lb., and the highest 63·25 lb. per unit. The last figure is probably a freak figure from a small station operating under abnormal conditions.

Now, if the whole of the energy produced by the 438 stations had been generated as economically as that at the station with the lowest consumption in group (*a*), i.e. with 18 per cent thermal efficiency, the resultant saving would have been fully 3½ million tons, or 47 per cent of the total consumption.

If allowance is made for those stations in group (*d*), generating 3 million units or under, which are so situated that they could not be included in a centralized scheme, we still have a possible saving of 3 million tons per annum, and this, if capitalized at the present price of coal on a 20 years' basis, would amount to no less than £90,000,000.

This saving is calculated on the present output of electricity. Taking into account the certain growth in output, which cannot be estimated at less than double the present output five years hence, the saving of our capital resources will be correspondingly greater.

The estimate of saving is based on a thermal efficiency of 18 per cent, a figure which has already been attained, and it is probable that an efficiency of even 20 per cent may be reached in the near future.

It is not sufficient therefore for the local station engineer to show that a case can be made out for continuance on commercial grounds. The question must be looked at from a much broader point of view. It is quite easy to show that the value of the coal wasted at a local station amounts to less than the capital charges and the losses on a transmission system, but the broader view will take into account that transmission systems consist chiefly of copper and lead, or copper and steel, materials with an indefinitely long life and considerable residual value. The wastage of coal on the other hand can never be recovered, and in wasting it we destroy at once the nation's capital and our greatest industrial asset.

The outlook for the electrical industry as a whole was never more promising than it is to-day. The rapid development during the war, and the application of electricity to many industrial purposes, such as steel smelting and chemical processes, which were only in the speculative stage a few years ago, have established the future of the industry on a thoroughly sound basis.

The manufacturers of electrical plant and apparatus have an unrivalled opportunity. The whole world is waiting for their productions. The problem of the moment is to increase production, so as to meet the needs of our own markets in the first place, and at the same time to re-establish our export trade, to enable us to pay off the heavy indebtedness arising from the war.

The combination of manufacturing interests which has recently taken place may do much to assist rapid production by organization and allocation of the work amongst the factories which they control. If they can assure also that the pooling of manufacturing and commercial resources will not destroy the stimulus to individual effort, that standardization to ensure mass production does not mean the rejection of new ideas, and that the benefits from reduced production costs will be shared by the purchaser, then the new conditions will be welcomed by the general body of the public.

There is no public body in the country to-day which wishes to place its contracts in any country but our own. The old conditions under which the prices of British plant for public power stations was fixed in Berlin, Zurich, or the United States, have gone for a long time, and it will be the manufacturer's own fault if they ever come back; but if the purchaser is to lose the protection afforded by foreign competition, he must have some assurance that the prices charged are fair and reasonable, having regard to industrial conditions in this country, and that the plant he is purchasing will be at least equal in design and performance to the best that can be obtained abroad.

Much of the labour unrest in pre-war days was due to the absence of machinery for adjusting and settling differences before they became acute.

We have that machinery now in the form of Whitley Councils, and a National Industrial Council for the electricity supply industry, presided over by our Senior Vice-Chairman, Alderman Walker, has been at work for some time past. The first District Council for the same industry has also been set up in the North-Western Centre.

We have also to consider a scheme of specialized training for our technical staffs. At present a man who is qualified in one direction rarely possesses the all-round training necessary to secure a responsible position in a power station or on a transmission system. A Sub-Committee of this Centre has been recently formed with the object of bringing together the technical college authorities, manufacturers, and power station engineers, with a view to providing a specialized training —technical and practical—for the young engineers intending to follow power station work.

The new Boards and the supply authorities must remember, however, that if the right kind of men are to be attracted, the salaries paid must be adequate for the training they have received and the responsibilities they have to undertake.

The vital need of to-day of the electrical industry is co-operation between all the various sections and interests. If supply authorities, engineers, manufacturers, technical staffs and labour will realize that the wisest form of self-interest is to work for the welfare of the whole body, the electrical industry will be able to take advantage of the greatest opportunity in its history, and to assist in reconstructing the industry of this great Empire, which never needed the best work of all her sons so much as she does to-day.

SOUTH MIDLAND CENTRE: CHAIRMAN'S ADDRESS

By C. C. Garrard, Ph.D., Member.

(Abstract of Address delivered at Birmingham, 10 *November*, 1919.)

ENGINEERING IDEALS.

Before beginning my address this evening I should like to thank the members very sincerely for the honour they have done me in electing me to be their chairman, which honour I would assure them I much appreciate.

The Work of the Institution in Relation to its Members.

The Institution has passed, in recent years, through very trying times, but has emerged from them rejuvenated and strengthened and ready for the great work which lies in front of it.

In the past the Territorial Centres, then known as Local Sections, unfortunately, due to their constitution, had but a restricted scope in which they could exert themselves in the work of the Institution. Owing, it may be said, largely to the efforts of this Centre this state of affairs has been changed. It therefore behoves the Territorial Centres to justify, by their work, the confidence which the Institution has reposed in them, and it is to be hoped that the South Midland Centre will take the lead in this movement.

Among the matters calling for urgent attention on our part is the resuscitation of the Students' Section and the formation of Sub-Centres at Leicester, Stafford and Rugby.

It is gratifying to be able to record a decline in the feeling of antagonism to the Institution which formerly existed in some quarters. It is of the very greatest importance that all electrical engineers who take a pride in their profession should support the Institution.

Most engineers will agree that the profession of engineering does not leave a man much time for speculation upon the general fitness of things. This mental concentration upon scientific and technical affairs, which is a characteristic of the engineer, has its advantages and disadvantages. While few joys can compare with the exhilaration produced by the sense of successful accomplishment of a difficult engineering problem, nevertheless the engineer feels at times that the injunction that virtue is its own reward has had too literal an application to his own profession. In other words, it too often happens that the labour and application necessary for engineering work fall upon his shoulders while the material reward, which is the direct result of his work, goes elsewhere. And it is easy to see why this is so. Absorbed, as he necessarily must be, in his work, the engineer's whole mind is given to the actual matter in hand, to making the machine work, to designing and constructing the apparatus and the like. By the nature of things, therefore, if the engineer be unaided by any organization to protect his interests, when he almost of necessity must neglect them himself, he is bound to suffer. Now it must be confessed that engineers have sometimes themselves condoned this unsatis-

factory state of affairs by accepting a degraded ideal of the work of an engineer. It is impossible to take a profit-making test as the sole criterion of engineering accomplishment; in fact it is just as impossible as it is in the domain of Art. As the world is constructed at present, it is generally possible to make more money by buying and selling bad pictures than by painting good ones, and the self-advertising writer of trash makes a fortune while many a conscientious author has a job to make both ends meet. While, however, we have to recognize the facts there is no need to acquiesce in them. Rather should it be the object of all organized bodies of engineers to protest against them and to endeavour to bring about a more just state of affairs. In other words, one of the prime objects of an Institution such as ours is to set up a true criterion of engineering work and to see to it that the reward of the engineer is in conformity with this rather than with the fortuitous and accidental commercial standards at present in vogue.

I have sometimes heard discussions take place as regards the comparative worldly prospects of the engineer and the man who follows a purely business career, it being stated that there is more chance of making money in the latter vocation than in the former. It is, of course, somewhat difficult to reason with people who use such arguments. A certain unity of fundamental principles is necessary for all profitable discussion. Such people do not understand that one of the most prized possessions of an engineer is the tradition of engineering achievement. This tradition must be in the safe keeping of an organization, and it is from this point of view that we must value the Institution, the members of which regard the approbation of their fellow members, in engineering matters, as of equal, or of greater value to them than the more or less accidental commercial success with which they may be attended.

While the prime function therefore of the Institution is the guardianship of the standard of electrical engineering accomplishment, it must not be forgotten that engineers must live by the exercise of their calling. The Institution must therefore act as a support for them in the assertion of the high status of their profession, and we must all rejoice to see that in recent years the Institution has become alive to its responsibility in this respect. Very much more, however, is necessary to be done in this direction.

Another aspect from which the value of the Institution can be appreciated is that it develops a broad-minded outlook in the attitude of its members to engineering in general. This is a day of specialization and each one of us must, of necessity, especially cultivate some particular corner of the vast field of engineering. There is danger in this of acquiring a narrow-minded point of view. I have sometimes been told by members of the Institution that they never, or rarely, come to its meetings because the papers deal with subjects not immediately concerned with their special everyday work. Such an attitude is deplorable. One has only to make a very casual examination of the lives of great engineers to find that they are always very extended and general in their outlook. A wide view of things is also necessary if one is to retain the elasticity of mind which is essential to carry out any mental work with efficiency. It is also surprising to find what hints and help one can obtain in one's own particular branch of work by a study of engineering applied in other directions. It must be admitted that there is a great danger on the part of engineers to adopt narrow views not only as regards their own profession but as regards the world generally. This is one of the reasons why the so-called "man of business" often scores a seeming success over the engineer.

Voices have not been lacking in recent years warning engineers that it is necessary for them, for example, to take a greater interest in municipal and national government and to reject the contemptuous attitude many of them adopt as regards such matters.

The question is sometimes asked: "What benefit do I obtain by becoming a member of the Institution?" But this shows the questioner's ignorance of the point at issue. The question should be rather: "In what manner would my membership enable me to help forward the cause of electrical engineering?" It must be remembered that the Institution is not a club, although it provides an excellent means for becoming acquainted with brother engineers, but it is a national Institution. The greatness of a national Institution, and ultimately the benefit accruing to the individual members, are measured by the work it does in the national interest. It might, I suggest, be profitable if we could for a few moments to-night consider the work of the Institution from this point of view and, in particular, I should like to direct attention to three special aspects of this question, as follows:—

(1) The national importance of bringing to bear the engineer's knowledge and training in the executive control of affairs.
(2) The permeation of industry and commerce by the scientific method.
(3) The promotion of standardization as regards both products and performance.

The Engineer and the Control of Industry.

Dealing with the first of my headings, there is no doubt that we are at the present moment face to face with a fundamental change in the relationships between the State and industry. Whether we like it or not the State will in future take a very active part in the control and running of trade and manufacture.

The great industrial problem to-day is the increase of output. To a large extent the old ingrained habit of hard working has been destroyed by the war. Moreover, it would seem that the stimulus which hitherto induced the workman to put forth his best efforts has lost its power and a new one must be found. Now if the State approaches its new tasks in its old spirit we have nothing in front of us but stagnation or decline. The tradition of the Civil Service, which has in the past carried on the business of government, has been that of administration, and in the production of mere administrators there is no doubt it has been very successful. Lord Haldane recently expressed the opinion that the Civil Service could administer any organization in the world whatsoever.

For industrial progress, however, something more than mere administration is necessary, and that is creative effort. Herein lies the function of the engineer, who is above all things a creator. Now, it may be argued, one could still go on under the old scheme with the administrator in charge and the engineer called in from time to time as a hired man, something like the man who comes to tune the piano, to do the creation when it is thought to be necessary. This same idea has been the curse of British industry in the past and it certainly will not do in the future. Even the workman, and according to Lord Robert Cecil rightly so, is demanding that his status shall be raised from that of an employee to that of a partner. If the engineer is to perform his function properly in the new society which we see arising around us, he must assume responsibility, as it is only this sense of responsibility which will stimulate his brains to do the work that is required of him.

As members of the Institution we must insist that the Institution adopts this attitude and is ready at all times to maintain it.

As an illustration of the kind of action that can be taken I cannot do better than read a letter addressed by the Chairman of the Engineering Council of America to President Wilson, urging the appointment of an engineer on the Interstate Commerce Commission, as follows :—

"The President,
The White House,
Washington, D.C.

Sir,

The transportation systems of our country are largely the creations of its professional engineers. This statement can be made without disparagement to the statemen, the financiers, the manufacturers, the lawyers, the educators, the mechanics, the labourers and many others, who, with the engineers, have contributed to the development of transportation. Through all stages of preliminary exploration, final survey, construction, upkeep, and operation, in financial management, and in adjustment of the relations of transportation to the public, the genius and knowledge of the engineer are essential. Not only in technical physical matters, but also in determinations of policy, his contributions have supplemented and must ever supplement those of other men. These declarations hold good for all the carriers of commerce, by rail, by highway, by water, by pipe-line, by wire, or by air. Hence, it follows that the body established by the Government to regulate the commerce, the carriers and the ways of communication, embracing so many engineering features, should number among its nine members, men of engineering training and experience.

Engineering Council, being aware of a vacancy on the Interstate Commerce Commission, begs leave to request the Chief Executive that in filling this vacancy, he give earnest thought to the selection of a man who, to his other qualifications, adds the training and experience of an engineer familiar with transportation problems.

Engineer members wisely chosen would bring to the investigations and deliberations of the Interstate Commerce Commission not only technical knowledge of great value, but also experience in executive duties, a judicial attitude gained through the direction of work under contracts, minds of analytical habits, familiarity with costs of construction and operation, experience in dealing with employees of many vocations, and integrity of thought cultivated by that inescapable obedience to the laws of Nature involved in the practice of this profession. The engineer's training fits him for that mode of thinking which is indispensable to impartiality of judgment. One important function of the Commission is valuation of public utilities and another is the determination of relationships and responsibilities of the management of such utilities to the public. No other body of men has given so extensive and so scientific consideration to these matters as have members of the engineering profession.

Council's purpose is not to further the interests of any individual or group, but solely to serve the nation by strengthening one of its most important regulatory bodies. Upon the wisdom, intelligence and courage of this Commission depends in large measure the commercial welfare of the country. It is believed that the engineering profession can and should contribute to the country's well-being through the channel of membership in the Interstate Commerce Commission.

Very respectfully,
J. Parke Channing,
Chairman."

No words of mine could express the ideas better that I wish to bring before the members to-night than those contained in this letter.

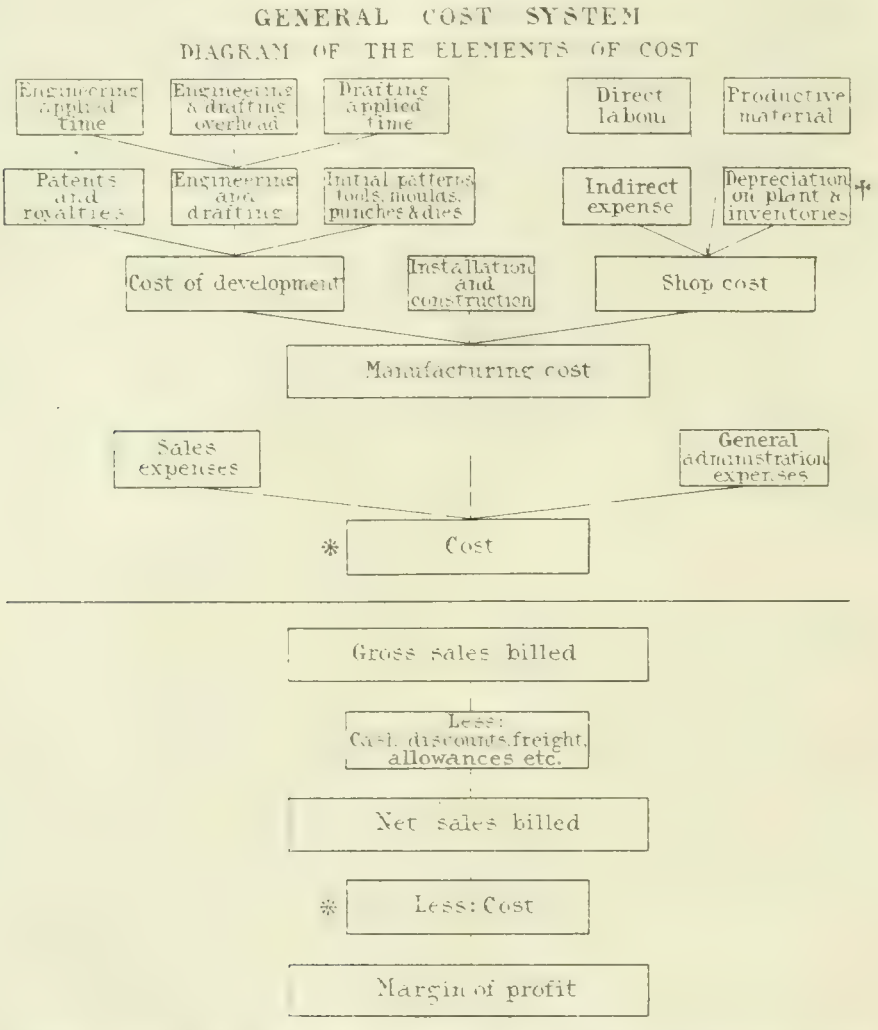
Scientific Costing.

Turning now to the second of my headings, the permeation of industry and commerce by the scientific method, I am afraid I would weary the members if I were to attempt to deal at all exhaustively with such a subject. I will therefore speak on one point only.

Now the basis of the method indicated is accurate measurement. The scientific investigator always proceeds along the path of careful measurement and comparison. In applying scientific methods to commerce and industry we do exactly the same; by means of statistics and accurate costing we obtain figures of absolute and relative efficiency and the data necessary for correct judgment. It is sometimes thought that cost-keeping is a mere matter of accountancy; but this is not so. The actual figures may be extended and added up by accountants, but the use and application of the costing in the engineering industry are matters for the engineer: they really constitute a chart recording efficiency meter. It is to be regretted that engineers have not given the subject of costing, as applied to engineering manufacturing, the attention it deserves. Costing as applied to the electrical supply industry is, of course, recognized as providing the ultimate test of the working of a supply station, which is judged finally upon the cost per unit generated. When we consider a manufacturing works, on the other hand, no such simple test can be applied. In the past, however,

competition has provided an alternative one. The costs have eventually affected the selling price, and that factory which could not sell cheaply had to close down. With the development of industry at the present day this kind of check is failing. Industry is becoming more and more organized and price competition between the different factories less effective. It is conceivable that a works, forming part of a large combination, could go on for years working in a most inefficient manner because it is protected from the crude, but effective, test of competition. With the organization of industry, therefore, and the limitation of competition, both, it may be said inevitable and beneficial tendencies, the development of scientific costing must go hand in hand.

The benefits of costing were shown to great advantage in the national factories erected by the Government during the war. With these, competition was out of the question as a means of suppressing the inefficient ones. In an interesting lecture, delivered to the London School of Economics by Mr. M. Webster Jenkinson, it was shown how costing took the place of competition. It, in fact, set up another kind of competition. In the lecturer's words "a friendly rivalry" was created between the various factory managers, the low costs obtained by the one being aimed at by the others.



* Wherever the term "cost" is used herein, it is intended to include all sales and administration expenses.
† Depreciation and indirect expense should be consolidated for absorption into shop cost.

FIG. 1.—Standardized Accounting and Cost System for Electrical Manufacturing Industry.

A similar cost competition will in the future replace the hitherto obtaining price competition in more and more branches of the engineering industry. In order that this may be effective, however, two things are necessary:—

(1) The details of costs will require to be published and publicly discussed.

(2) The cost keeping at the various factories must be conducted according to a common principle.

As regards the first condition the engineering industry is hardly in a condition at present to agree to it. Nevertheless there is no doubt that much greater publicity as regards such matters will be usual in the future. Indirectly such publicity would have a very good effect in showing everybody where the main items of cost are incurred. It might do something to help dissipate the erroneous notion, still industriously propagated, that manufacturing is a system whereby the workman is robbed of the greater part of the product of his labour. It is in this way, there can be no doubt, that a good deal of the industrial unrest at present handicapping trade can be removed. Every manufacturer has got to face the demand of labour for a voice in the control and direction of industry. If this demand is answered by a simple negative, I am afraid disaster will result. The only safe road is to work incessantly for a true co-operation between labour, capital and management, and a necessary preliminary step is to place upon the table the true economic facts governing the situation. Certain trades already have taken steps in the direction indicated. According to Mr. Edward Elbourne the frank discussion of costs with labour in the Pottery Trade Industrial Council " promises a new era of prosperity for what was one of the worst organized and worst paid trades in the country."

The second condition mentioned is necessary as it would be useless comparing costs in various factories if these are not obtained by the application of a common principle.

The Standardization of Methods of Costing.

A considerable amount of work has been done in the United States with the object of securing such uniformity in cost-keeping methods among electrical manufacturers. The Federal Trade Commission of Washington took the lead in July 1916 by issuing a pamphlet on " The Fundamentals of a Cost System for Manufacturers."

About the same time a committee was set up representing the American electrical manufacturing industry in order to evolve a standardized system of accountancy and costs which would be applicable to both the large and small firms. This committee's report has been approved in 1917 by the Federal Trade Commission and is being carried into effect by a large number of American firms. Fig. 1 illustrates the scheme which has been adopted. One important point has, I think, been omitted in this proposal and that is the inclusion of interest on capital as an item of cost. In my opinion this should be arranged for, which would leave profit as an additional return or dividend. The standard percentage of interest on capital would have to vary from trade to trade, and in fixing it the hazard or risk of loss in the business would have to be taken into account. The advantages that this action would have in enabling reliable statistics and data to be prepared applicable to the whole of the industry are apparent. We have to recognize that the days of pure individualism are over, and that progress in the future will depend more and more upon co-operative effort. The standardization of accounting and costing would, I am convinced, help forward this ideal in no small measure, and for this reason I have drawn attention to the matter in this Address. It may be added that steps along the lines indicated have been taken already in this country in the printing and pottery trades.

The Promotion of Engineering Standardization.

It is now universally recognized that a great extension of the idea and practice of standardization is necessary if the problems in front of the engineering trade and profession are to be solved. This has been, there can be little doubt, recognized by our late enemies. During the war a body known as the " Deutsche Industrie Norm " was formed in Germany to advise in the matter of uniformity of pattern and method of manufacture as regards the whole industry of the country. A special journal was issued, and these activities are, I understand, continuing at the present time. In other countries also a similar movement is taking place. Hitherto, in this country, the idea of standardization has, to too great an extent, been confined to settling upon agreed dimensions of parts and the like. Standardization, however, properly understood, covers a much wider field including the standardization of methods of manufacture and the fixing of standards of quality and performance. In such work our Institution should take a leading part, and in this connection some remarks made by General William H. Bixby in his presidential address to the American Society for Testing Materials on 25th June, 1917,* are interesting.

These were as follows :—

" The discussions of engineering questions and their conversion into formulæ, specifications, or other standards, through the work of committees, are becoming to-day more and more the most important features of engineering societies. In short, the engineering society of to-day which is the most important and most useful and most valuable to everybody concerned, is the one which gives the most beneficial results to the general public rather than to the individual members."

These remarks of General Bixby will, I am sure, be agreed to by all members of this Institution and I should like to direct their attention specially to the first part of the quotation as I consider it indicates a path along which the Territorial Centres can exercise an increasing usefulness. The Institution has, in collaboration with the other engineering societies, set up the Engineering Standards Association as the authority for engineering standardization in this country. It would be a mistake, however, to leave everything to the Association. The spade work, and especially the propaganda, must to a large extent be done outside it. The necessity of this becomes more apparent if the question be regarded from the wide point of view as is done by General Bixby.

It might be as well here to consider for a moment the idea, still very common, that standardization retards progress. This fallacy was dealt with very effectively by a writer recently as follows† :—

" Standards do not restrain improvement. On the contrary, if rightly understood, they promote improvement. In any well ordered works improvement becomes a specialized branch distinct from manufacture.

* *Proceedings of the American Society for Testing Materials*, 1918, vol. 18.
† Alfred Herbert, Ltd., *Monthly Review*, Oct., Nov., Dec., 1918.

Special attention is given, by a special man or staff, to alteration of design and to complaints and suggestions from users. If the design is full of diversity there is no basis for improvement. As soon as it is standardized it becomes possible to localize faults. Some article turns out in use to be too weak or too long or too small in diameter. If the article was made in a diversity of strengths and sizes and quality of material, there is no telling whether or how it should be altered. Perhaps the complainant was merely unlucky in getting a short one or a weak one. As soon as it is proposed to set standards the designers are put on their mettle to find the right properties. If experience shows that their first efforts are in error they amend the standard. If the amendments are too frequent an investigation will probably take place to see whether such amendments were really justified by new circumstances, or were due to lack of care or skill in the earlier changes. Thus an incentive and an absolute premium are put on improvement."

America, formed the American Engineering Standards Association which, it is intended in future, shall be the ultimate American authority on engineering standardization. The Materials Society, however, will continue its special work subject to the ultimate control of the Engineering Standards Association. The work of the Society for Testing Materials is of the utmost value. In particular its constitution, widely extended membership and practice of holding meetings for discussions, are particularly helpful in arriving at, and in the discussion of, the standards which the Society is responsible for.

As an instance of the need for standardization of materials I would instance the case of brass. Birmingham is the centre of the brass trade of the world, and yet as far as I am aware there is no authoritative definition in this country as to what brass actually is.

As illustrating the work of the American Society for Testing Materials it may be pointed out that in 1919 it issued standard specifications for cartridge brass,

A.S.T.M. Proposed Specification for Brass Ingot Metal for Sand Castings.

Alloy Grade Number	Copper, per cent	Tin, per cent	Lead, per cent	Zinc, per cent	Iron, Maximum, per cent	Antimony, Maximum, per cent	Aluminium, per cent	Sulphur, Maximum, per cent
1	86	8	3*	3	0·25	0·25	None	0·05
2	85	5	5	5	0·35	0·25	None	0·05
3	83	4	6	7	0·35	0·25	None	0·05
4	77	3	10	10	0·40	0·35	None	0·05
5	76	2	6	16	0·40	0·25	None	0·05
6	65	1*	2	33	0·50	0·20	None	0·05
7	60	1½*	3	37	1·00	0·20	None	0·05

* Maximum.

Fig. 2.

Few people realize the great amount of work entailed when a panel or committee sets out to standardize quite a simple article. To attain success its members must be inspired by a veritable passion for the work. Cases are not unknown, however, where people have got themselves elected on such standardizing committees more with the object of hindering standardization than of promoting it. Such members have to be treated with a firm hand.

It is a mistake in standardization work to attempt to attain absolute perfection at the first trial. This results in very lengthy delays occurring in the issue of specifications. The method adopted by the American Society for Testing Materials of issuing tentative specifications has much to commend it. When issued in this way they are immediately subjected to practical tests and criticisms and any weaknesses are soon found out, or improvements suggested; thus much more rapid progress can be made.

The standardization of the quality and testing of materials could be considerably extended with advantage in this country. In the United States this has been the special province hitherto of the American Society for Testing Materials. This Society has now, in conjunction with the other engineering Institutions of

cartridge brass discs, naval brass rods for structural purposes, and standard methods for the chemical analysis of manganese bronze and the chemical analysis of gunmetal. Recently, moreover, a complete range of standard mixings for brass castings has been issued which should prove of the utmost value (see Fig. 2).

Standards of Quality and Performance.

In the past the standard of quality and performance has mainly been a matter of tradition. Standards of workmanship, for example, have been handed down from workshop to workshop. The method whereby this kind of thing can be put upon a sound basis, however, is illustrated in B.E.S.A. Specification No. 25 on "Errors in Workmanship." The necessity for fixing a standard of quality and performance is shown by the war which, by its disorganization and destruction, has appreciably lowered the standard of many industries and has provided a possibility of a permanent loss in some instances of the former high standard altogether.

Many of the Bulletins issued by the American Bureau of Standards are excellent examples of the standardization of performance.

Almost the only similar things with us are the Institution Wiring Rules and the Factory and Workshop

and Mining Regulations. There is a vast field of work for us to cover in the extension of these. In practically all branches of engineering we still rely to a very large extent upon personal opinions and judgments as to what constitutes a good job or vice versa. "A good engineering job," however, is as capable of being as accurately defined as, for example, the temperature rise of a dynamo, and it should be one of the main objects of Institutions such as ours to discuss such standards with a view to the levelling up and fixing of the same.

It is intended during the forthcoming session to have a discussion one evening on some of the specifications issued by the B.E.S.A. This, in my judgment, should be a permanent feature in all future sessions so that the specifications as they are issued should come up automatically for discussion by the members.

I should like to add that it seems to me that this matter is of such importance that a special committee should be set up by the Council to deal with the same. At present we have the following five Sectional Committees for Electric Traction, Electricity in Mines, Electro-Chemistry, Lighting and Power, and Telegraphs and Telephones. These committees investigate progress in the subjects assigned to them, and take such steps that the Institution has brought before it particulars of all new developments.

Using a military simile they perform the function of the advance guard of an army. The committee I suggest, however, would be concerned with the consolidation of the position from time to time, in fact would carry out the work described above by General Bixby.

It is somewhat difficult to find a suitable name for such a committee. For the want of a better one I suggest "Standardization and Recommended Practice Committee." Its work would not clash at all with that of the Engineering Standards Association, but would be confined to promoting discussions on, and recommending, the use of the specifications when issued, and for the preparatory work which is necessary to be done to enable the Standards Asociation eventually to prepare the actual specifications. It would also serve as a means of obtaining collective solutions of many problems which are unsolved at present because the information which would provide the solution desired is scattered, and therefore to a great extent valueless.

In conclusion I would say that I hope I may have said something which may help, more especially the younger members, to set up for themselves a high ideal of the work of their profession, and to indicate a few directions in which the Institution, to which we all are proud to belong, may be moved to support that ideal.

THE CALCULATION OF TOOTH RELUCTANCE: A SUGGESTED IMPROVEMENT OF HIRD'S METHOD.

By S. Neville, B.Sc.

(*Paper received 27 March, 1911.*)

The object of this note is to describe a modification of Hird's method of calculating the excitation required for the teeth in electrical machinery, which gives a much more accurate result for highly tapered or for saturated teeth, yet is equally simple in use.

In the original paper * two methods are proposed. One of these involves no mathematical approximation, and therefore yields a perfectly correct result, in cases where radial ventilating ducts are not employed; but it is unfortunately too complicated for everyday use and is not capable of the same accuracy when radial vents are present.

The other process, which is the one in more common use and generally known as Hird's method, is based upon the assumption that, in any tapered tooth, the apparent flux density varies uniformly over the length of the tooth. That this is never entirely true can be realized from the fact that the *apparent* density is at every section inversely proportional to the tooth width, which itself varies uniformly; and the extent of the discrepancy can be seen from Fig. 1, in which the curve marked K=1 shows the actual variation of apparent density over a tooth 10 cm. long, tapering in width from 4 cm. down to 2 cm. and carrying a flux of 0·6 megaline per cm. length of core. The result is that, for a highly tapered tooth, the method gives much too high a value for the excitation required; and generally sufficient accuracy can only be obtained by dividing the tooth into several sections and treating each separately.

The remaining curves of Fig. 1, however, show the manner in which the *true* density in the iron varies over the length of the tooth for different values of K at the root of the tooth, where K denotes the ratio of the total area of iron and air to the net area of iron alone. It will be noticed at once that for all customary values of this ratio these curves approximate very fairly to straight lines; and that even for K=1·5 and K=5 (which values are beyond the usual range of practice) the curves of true density are much more nearly straight than are those of apparent density. It will also be found that very similar results are obtained whether K be due entirely to the slots, or partially to radial vents.

* W. B. Hird: "The Reluctance of the Teeth in a Slotted Armature," *Journal I.E.E.*, 1900, vol. 29, p. 933.

It will therefore be evident that if from the apparent densities the true densities at the two ends of a tooth be first determined, Hird's simpler method can be applied directly to these values with a very nearly correct result in all cases.

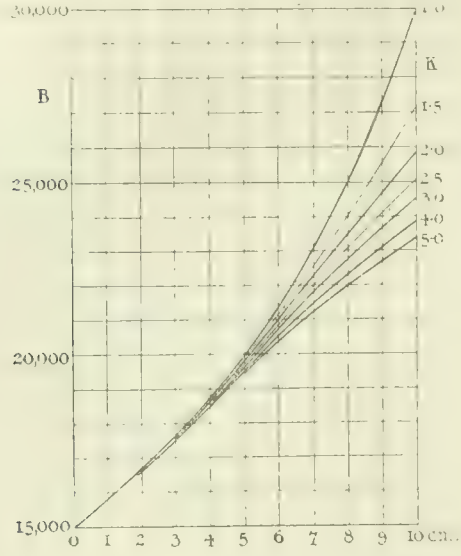


FIG. 1.—Variation of flux density in tapered tooth.

A convenient arrangement for this purpose is illustrated in Fig. 2. The curves marked K=1 to 4 show the relation between the apparent density B′ on the lower horizontal scale and the true density B on the vertical scale. These are readily deduced from the ordinary magnetization curve if a few points be calculated from the expression $B' = B + 1{\cdot}257\ (K-1)\ a\ t$. The remaining curve is constructed exactly as in the original method; namely, by integrating the magnetization curve with respect to B as variable, and plotting the integral a on the upper horizontal scale as a function of B on the vertical scale.*

Then, taking any two apparent densities of B'_1 and B'_2, the corresponding real densities B_1 and B_2 are read off from the curves for the appropriate values of K_1 and K_2; and, proceeding on to the integral curve with these same ordinates, the values of a_1 and a_2 are determined. Then the average excitation per cm. is given by the simple formula

$$a\ t_m = \frac{a_2 \quad a_1}{B_2 - B_1}$$

Thus, in the example quoted, assuming a parallel slot 2 cm. wide and one 10 mm. radial vent per 5 cm. length of core, the calculated data are:

$B'_1 = 15{,}000, \quad K_1 = 1{\cdot}88;$
$B'_2 = 30{,}000, \quad K_2 = 2{\cdot}50.$

Hence, from Fig. 2, $B_1 = 15{,}000, \quad a_1 = 0{\cdot}05 \times 10^6;$
$B_2 = 25{,}100, \quad a_2 = 6{\cdot}05 \times 10^6;$

and therefore $$a\ t_m = \frac{(6{\cdot}05 - 0{\cdot}05)\ 10^6}{25{,}100 - 15{,}000} = 594.$$

* It may be mentioned that in the original method it is necessary to perform the integration separately for a number of values of K.

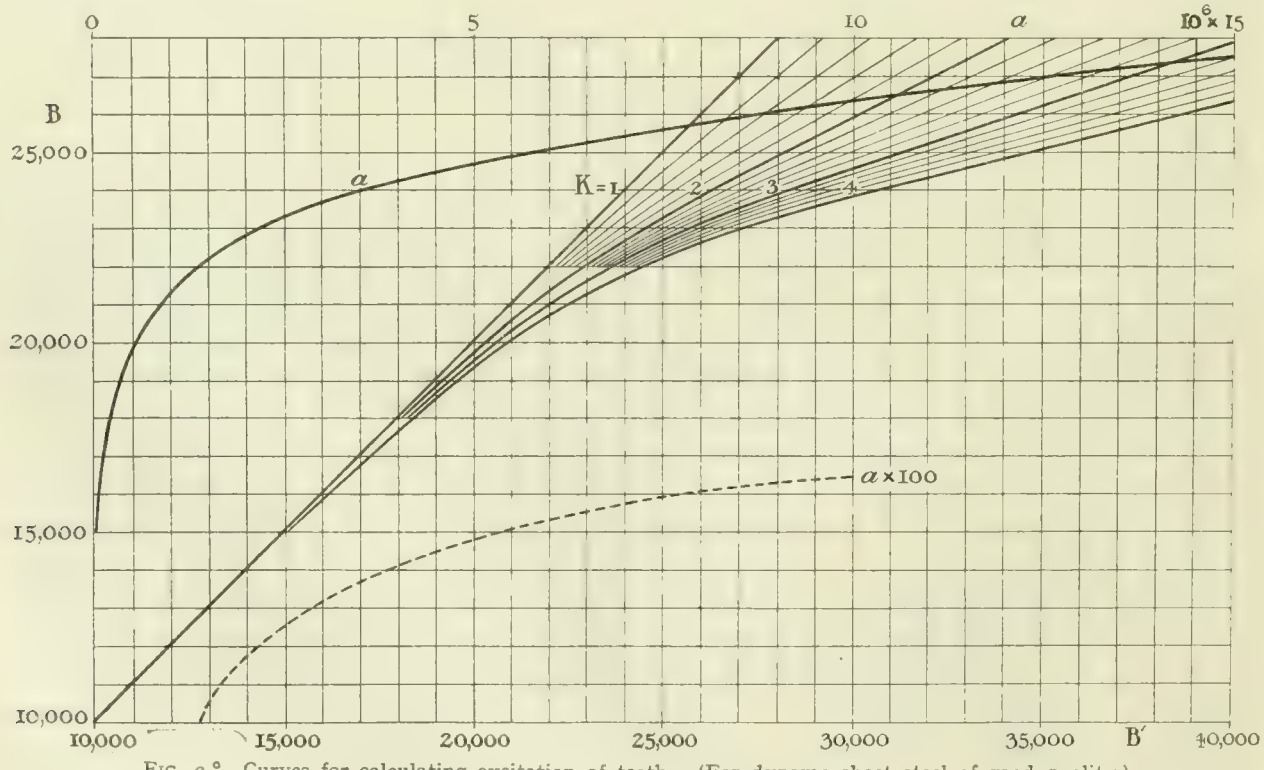


FIG. 2.*—Curves for calculating excitation of teeth. (For dynamo sheet steel of good quality.)

* Based upon the magnetization curve given by Professor Miles Walker in "The Specification and Design of Dynamo-Electric Machinery," 1915, p. 42.

The value obtained by calculating the excitation per cm. at a large number of sections and averaging graphically is $a\,t_m=581$, and this can be regarded as fairly exact; consequently, with the .proposed method, there is no necessity for dividing the tooth into smaller sections.

The result obtained in the above example by the direct application of Hird's method to the complete tooth is $a\,t_m=823$, which is more than 40 per cent too high. By dividing the tooth into two parts and repeating the calculation for each, the error could be reduced to about 10 per cent; but for greater accuracy still further subdivision and labour would be necessary.

PROCEEDINGS OF THE INSTITUTION.

638TH ORDINARY MEETING, 13 NOVEMBER, 1919

(Held at the Institution of Civil Engineers.)

Mr. C. H. WORDINGHAM, C.B.E., Past President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting of the 30th June, 1919, were taken as read, and were confirmed and signed.

A list of candidates for election and transfer approved by the Council for ballot was taken as read, and was ordered to be suspended in the Hall.

The following donations were announced as having been received, and the thanks of the meeting were accorded to the donors:—

Benevolent Fund.—H. S. E. Austin, L. Birks, M. Farrer, R. D. Gifford, J. S. Hasdell, Messrs. W. T. Henley's Telegraph Works, Ltd., R. M. Longman, T. B. L. Newstead, W. Redman, and The "Twenty-Five" Club.

Library.—The Admiralty, D. A. Bremner, The British Electrical and Allied Manufacturers' Association, The British Engineers' Association, The Canadian Government Trade Commissioners, A. A. C. Dickson, A. B. Eason, *Electrical Review*, The Engineer-in-Chief of the G.P.O., E. Garcke, C. C. Hawkins, The Lancashire and Cheshire Coal Research Association, Lloyd's Registry of Shipping, Prof. W. MacLean, D.Sc., The Marconi Wireless Telegraph Co., Ltd., J. W. Meares, The Meteorological Office, The Japanese Ministry of Communications, J. D. Morgan, Messrs. S. Rentell R. & Co., Ltd., The Royal Aeronautical Society, Prof. Stanley, A. Still, Messrs. E. & F. N. Spon, Ltd., The Syndics of the Cambridge University Press, S. F. Walker, Prof. R. M. Walmsley, D.Sc., and A. P. Young.

The Premiums (see *Journal I.E.E.*, 1919, vol. 57, p. 325, and *Institution Notes*, August 1919, No. 15, p. 33) and Scholarships (see *Institution Notes*, December 1919, No. 16, p. 2) awarded during the Session 1918–1919 were then presented by the chairman to such of the recipients as were present.

The CHAIRMAN: It is now my pleasant duty to ask the new President, Mr. Roger T. Smith, to take the chair.

The chair was then vacated by Mr. Wordingham and taken by Mr. Roger T. Smith amid applause.

Mr. W. M. MORDEY: I am sure we all part from Mr. Wordingham as President of this Institution with great regret. In the first place I should like to condole with our new President on having to follow one whose great ability and tremendous energy and activity have made it very difficult adequately to follow him in the chair. He has been President for two years, and during that period has done a very great deal—perhaps I may say more than any president we have ever had—to increase the influence, the usefulness, and the importance of the Institution. Some of us, perhaps, could not follow him altogether in some of the extensions of the activities of the Institution which he inaugurated and carried into effect, but those of us who may not altogether have agreed with him in every respect have been in a minority and therefore no doubt wrong. Anyway, instead of the Institution now confining itself, as hitherto, mainly to the more or less calm discussion of engineering and scientific questions, it covers a very much larger field of activities. I think I may say that Mr. Wordingham's record of work speaks for him far more eloquently than anything I can say. We have been glad to see him carrying on the traditions and the work of one of our older and highly esteemed and honoured Past-Presidents, the late Dr. John Hopkinson, under whom he began his professional life as a student and assistant. Since then he has always occupied positions of great honour and responsibility, always with credit to himself and to the satisfaction of those with whom he has had to deal. I will not take up any more time, but will read the words of the formal resolution that I have to propose, merely saying that in passing this resolution very heartily, as I am sure it will be passed, we do so in no formal spirit but with feelings of gratitude for the self-denying and arduous work that Mr. Wordingham has done as President of this Institution. I have the greatest pleasure in moving: "That the best thanks of the Institution be accorded to Mr. Wordingham for the very able manner in which he has filled the office of President during the past two years."

Mr. W. B. WOODHOUSE: I have great pleasure in seconding the resolution which Mr. Mordey has proposed. There is very little I need say with regard to Mr. Wordingham's tenure of office as President; it stands on record in the *Journal*, in the growing membership of the Institution, and in the wider and

wider recognition which the Institution is receiving from all quarters. Mr. Wordingham's enthusiasm and energy have carried the Institution forward so much that when we come to look back in a few years' time we shall realize perhaps even more fully than we do to-day the very valuable work he has done.

The resolution was then put by the President and carried with acclamation.

Mr. C. H. WORDINGHAM: I thank members from the bottom of my heart for the very kind way in which this vote of thanks has been proposed, seconded, and received. The work of the President is very heavy—far heavier, probably, than those who have not filled the office can realize. It has been essentially a labour of love, and it has been a source of intense satisfaction to me to be able to serve the Institution of which I am so proud. I should like to say one word of thanks to the two Councils with which it has been my privilege to work. They have supported me splendidly in every way. They have been unsparing in attending long and frequent meetings, both of Council and of Committees. No President could have had better support than I have received from the two Councils that have been in existence during the last two years. It would be invidious to mention names, but I feel that I must say one word of gratitude to Mr. Sparks for the way in which he supported me when I took over the reins of office from him, and has continued to support me ever since. The position of Past-President is one of extreme difficulty and delicacy. On the one hand he must not drop suddenly all he has been doing, and on the other hand he must not be unduly obtrusive. Mr. Sparks has backed me up in every way, even when, perhaps, he has not personally seen quite eye to eye with my proposals. I can only hope that I shall do one-quarter as well as Mr. Sparks in fulfilling a similar office in regard to our new President. I can promise him that he shall have my most hearty support in everything that he thinks is good for the Institution during his term of office.

The President then delivered his Inaugural Address (see page 1).

Mr. C. P. SPARKS: I have to propose "That the best thanks of the Institution be accorded to Mr. Roger T. Smith for his interesting and instructive Presidential Address, and that, with his permission, the Address be printed in the *Journal* of the Institution." As a student and as member of the various classes of the Institution I have listened to the Addresses of the Presidents for the last 35 years and, personally, I am fascinated by the Address which has been delivered this evening by our new President. In the first place, I wish to congratulate him on his tact and on the manner in which he approached the subjects with which he dealt. As one of your Presidents during the war period, I was naturally pleased to hear the President place in the forefront of his Address the question of the employment of disabled soldiers and sailors, a subject to which I gave and still give attention. It was interesting to me to hear Mr. Roger Smith, who is a practical engineer, emphasize the importance of improving our present methods of engineering education in every possible way. In the next place, the President has given us a most interesting résumé of the present position in regard to railway electrification, and I am sure we shall all read in the *Journal* with the greatest possible interest the details which he has promised us. There is, however, one point to which I should like to refer and which at present I do not quite grasp. I speak rather as a member of the public than as a member of the Institution. As I understand it, the President lays down the proposition that railways are run to meet the traffic requirements; that engineers must meet the requirements of the public; and that the public has to be educated with regard to the possibilities of electricity. I have lived for many years in the suburbs of London, and when I travelled to London by a slow method of locomotion, viz. steam, I travelled in comfort. I got a seat to which I was entitled, every day, in a first-class carriage with five other passengers. But we have now got an electric service, and the possibilities of transportation have increased so much that the demand for seats is 75 or 100 per cent more than it was before. But look at the effect on the public: 16, 17, 18, 19, or 20 people have to travel in one compartment, and it has become quite unbearable. Those of us who are fortunately situated can come up to London in our motor-cars. During war-time we put up with the stress and strain, but we cannot go on for ever in this way. In the old days I used to take one hour to get from my home to the office; it now takes one hour and 20 minutes with all the standing up and other inconveniences; so that I have been compelled to use the road, and I save 20 minutes each way by not using the railway. It seems to me that there is something wrong somewhere. I am not blaming the electric side, but the facilities are so great that something must be done in order to rectify the present state of affairs. In conclusion I should like to thank my friend, Mr. Wordingham, most cordially for his generous expression of appreciation of any assistance I was able to render him during his Presidency.

Mr. J. S. HIGHFIELD: It gives me great pleasure to second the vote of thanks to our President which has been so ably moved by Mr. Sparks. I agree with everything Mr. Sparks has said about the President's most able Address, which I am sure will make a valuable addition to the *Journal*. One point, which Mr. Sparks has not mentioned, particularly interested me, namely, the President's reference to the necessity of the adoption of the greatest sympathy and skill in arranging relations between masters and men. The war has torn down the traditions of society. It is the business of all educated men to assist in building them up again and I am sure that the President's principle of skilful sympathy is the means to adopt.

The resolution was put to the meeting by Mr. Wordingham, and was carried with acclamation.

The PRESIDENT (*in reply*): I thank the members very much for their cordial vote of thanks. Mr. Sparks has given me an ideal of performance which I will try to live up to, but in the meantime I can only refer him to a label which obstructs the view from the tube trains but which gives an explanation—or is supposed to give an explanation—of why things are as they are.

The meeting adjourned at 7.30 p.m.

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THE DESIGN OF MULTIPLE-STAGE AMPLIFIERS USING THREE-ELECTRODE THERMIONIC VALVES.

By Professor C. L. FORTESCUE, Member.

(*Paper received* 30 *October, and read at a* WIRELESS SECTIONAL MEETING *of the* INSTITUTION, 19 *November*, 1919.)

INTRODUCTORY.

The methods given in this paper were developed in the course of working out the design of valve amplifiers for use for naval wireless-telegraphy purposes, and permission to publish this paper has been specially given by the Admiralty. The author is indebted to various co-workers for numerous suggestions which led finally to the form given. A vast amount of experimental work on the subject was carried out at H.M. Signal School, Portsmouth, by Lieutenant J. K. Catterson-Smith, R.N.V.R., and Lieutenant W. A. Appleton, R.N.V.R. Many suggestions were made at different times by Mr. H. A. Madge and Mr. Gossling, at Signal School, Portsmouth, and by Captain H. J. Round of the Marconi Company.

Latour * has already published a method of dealing with single-step amplifiers and for determining the best circuit conditions. Other papers, too, have appeared in various technical papers. but it is believed that this is the first attempt to deal comprehensively with the problems of the multiple-stage amplifier. Even here the case of the employment of a step-up transformer between valves has had to be omitted owing to the complexity of the conditions.

Beyond a single valve the formulæ become very involved in even the least complicated cases. It has not been found advisable to attempt to simplify them, but they have been left in a form admitting of fairly quick numerical calculation for any given conditions. With a little experience a very few numerical calculations enable the required conditions for any particular design to be arrived at.

It should be added, also, that the problems dealt with are only those relating to the pure amplifying action. No attempt is made to deal with such questions as the action of the rectifiers, the circuit arrangements for use with amplifiers, the source of "valve noises," the use of limiting valves, or any other of the numerous problems met in the design of the complete set of apparatus of which the amplifier is a part only.

* *Electrician*, 1916, vol. 78, p. 280.

(A) DESCRIPTIVE.

(1) *The simple case of a single valve used as a resistance amplifier.*—The simplest amplifying circuit is that shown in Fig. 1. Here A, G, and F are the valve electrodes, the anode, grid and filament respectively. The filament temperature is maintained by current from the battery B_1 and controlled by the adjustable resistance R_1. A steady potential is maintained between the anode and filament by the battery B_2, the anode current passing through the anode resistance R_A. The small potential variations to be magnified are superimposed upon the steady voltage maintained by the battery B_3 between the negative terminal of the filament and the grid. These variations may be looked upon as being produced by a tiny alternator D, representing the input circuit. Under these conditions the potential variations consist of a rise above and fall

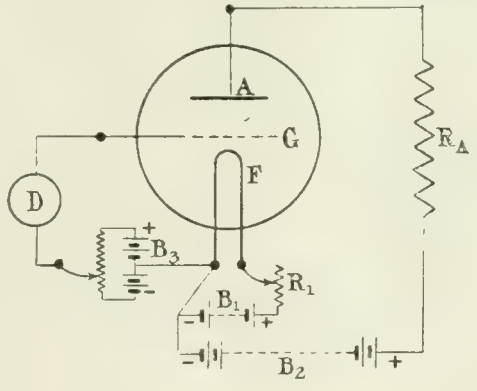

FIG. 1.

below the mean potential of the grid relative to the negative end of the filament. The changes of the grid potential are immediately followed by changes of the anode current, which in turn are accompanied by changes of the anode voltage due to the change of potential difference across the resistance R_A.

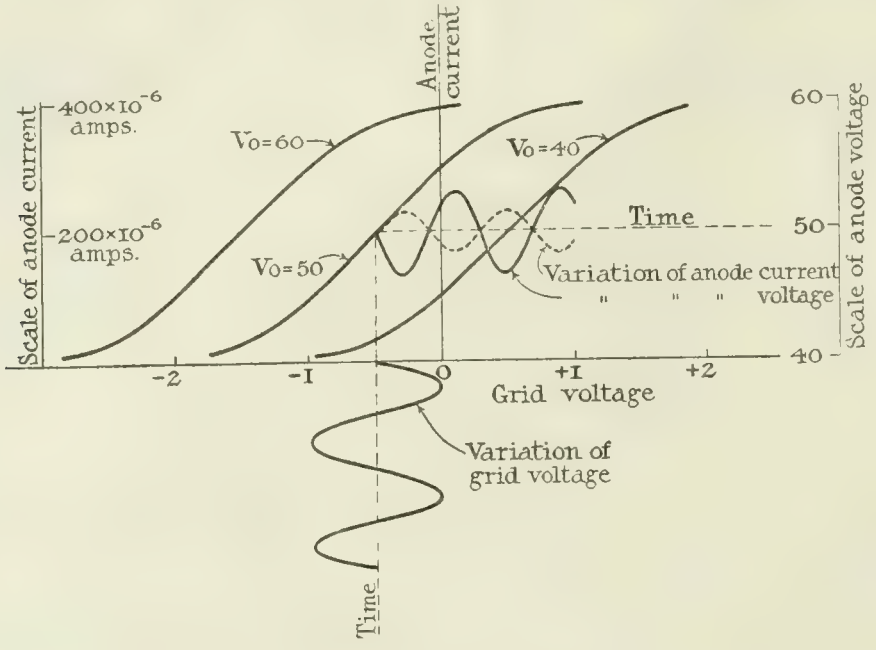

FIG. 2.

The curves of Fig. 2 show these variations and their relative phases, it being assumed that the variations of potential applied to the grid are more or less sinusoidal in form and of constant amplitude. The relative values of the alternating component of the voltage across R_A and the alternating grid voltage give the voltage step-up of the valve and circuit.

With this arrangement of pure resistances throughout, the variation of the voltage across R_A can be made an exact reproduction of the variations of the grid voltage, provided that both are small compared with the range of voltage corresponding to the active portions of the characteristics.

(2) *Use of tuned circuits instead of resistances.*—For low-frequency changes the conditions of the previous paragraph can be realized without difficulty. But capacity effects are serious at high frequencies (radio frequencies) and the resistance R_A may be replaced by a condenser and inductance in parallel as in Fig. 3, the circuit being accurately tuned to the frequency of the variations of grid potential.

If L_A is the inductance and R_A the effective high-frequency resistance of the tuned circuit, then to a sustained alternating current this circuit behaves as a non-inductive resistance of $\omega^2 L_A^2/R_A$ ohms, where $\omega = 2\pi \times$ frequency.

To a sustained oscillation this circuit behaves in the same way as the resistance circuit of Fig. 1. But to an oscillation of varying amplitude the behaviour is quite different. For example, during the first few cycles after the oscillation is applied to the circuit the current flowing round the circuit L_A C_A has not been built up to its normal value and the effective amplification is less than is the case at the later stages.

(3) *Selective and non-selective amplifying.*—With a circuit such as that of Fig. 3 the tuning of the condenser C_A becomes more and more critical as the resistance R_A decreases. The more critical the tuning the less will be the relative amplification at frequencies other than the frequency to which the circuit is tuned. An efficient circuit consequently leads to a selective amplifier. The

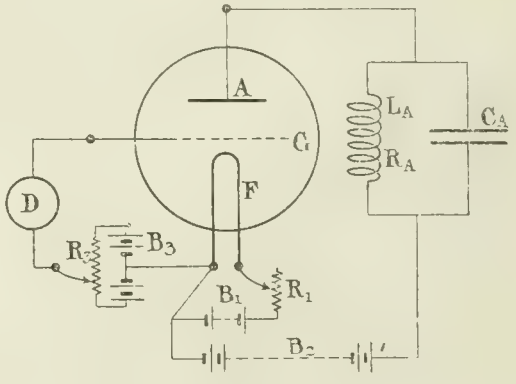

FIG. 3.

effective damping of the circuit can be regarded as being made up of two parts, viz. (*a*) the resistance of the circuit itself; and (*b*) the equivalent resistance due to the resistance of the tube in parallel with the circuit. This latter component decreases with a decrease in the ratio of L_A/C_A, and vice versa. With large values of L_A/C_A it constitutes

the principal cause of the damping and may render the circuit almost aperiodic. Thus a circuit having a very high ratio of L_A/C_A cannot be efficient, and is the reverse of a selective amplifier.

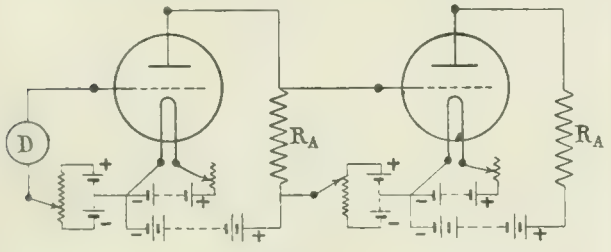

Fig. 4.

In practice the conditions may make either one or the other of these conditions desirable. Where high selectivity is essential and tuning is not objected to, the efficient circuits may be used. But where approximately equal amplification is required over a wide range of frequency, then a high ratio of L_A/C_A and a valve of low effective anode resistance would be used.

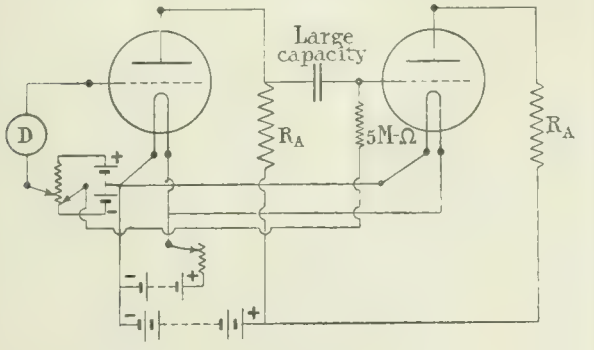

Fig. 5.

(4) *Cascade amplifying.*—Multiple-stage amplification can be obtained with either of the arrangements of Figs. 1 or 3, the anode-circuit voltage variations of each valve being applied to the grid of the valve next in the series, and so on.

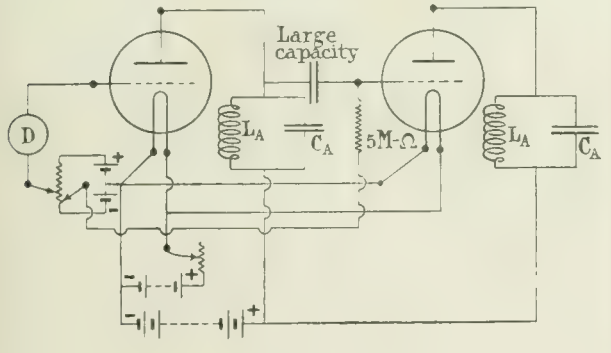

Fig. 6.

Fig. 4 shows a possible arrangement of two valves in cascade using resistances in the anode circuit. Separate filament and anode batteries are required with this arrangement. In Fig. 5, however, almost the same results are obtained without this disadvantage. A similar arrangement for two valves with tuned anode circuits is shown in Fig. 6.

A cascade arrangement of valves with step-up transformers between the valves is another possible combination and is shown in Fig. 7. When allowance is made for the self-capacity of the windings this circuit is very closely allied to that of Fig. 6.

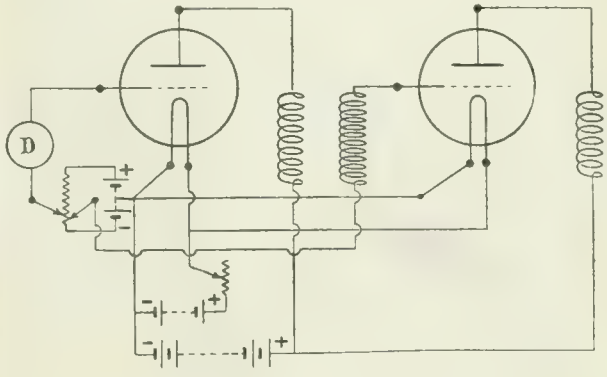

Fig. 7.

At first sight it would appear that this process could be continued indefinitely and that an infinite amplification could be obtained. There are, however, limits which will be discussed later.

(B) "Reaction" Effects, and the Tendency for Alternating Currents to be Maintained in the Circuits Connected to the Tubes.

(1) *Reaction effects due to electrical coupling in the amplifier.*—The action of any amplifying system, electrical, mechanical or otherwise, is strongly affected by any transfer of energy back from the output end of the system to the input end. With the amplifiers now under discussion, the transfer back of energy may be caused by any form of coupling between the output and input circuits. If this coupling is such that the changes at the input end are accentuated, it follows that changes of a given amplitude in the input circuit can be maintained by a smaller external power supply. In the extreme case the coupling may be strong enough to do more than maintain the changes at the input end. The system is then unstable, and if the circuits consist of inductances and capacities, oscillations will be set up and maintained. If there are no inductances or capacities, the voltages and currents will steadily change in one direction or the other until the altered slope of the characteristic curves stops the action.

On the other hand, the coupling between the ends of the system may tend to oppose the changes at the input end. More power is required then from the external source to maintain the changes in the input circuit, and the effective amplification is reduced. Obviously, the greater the opposition coupling, the poorer will be the amplification obtained.

In an arrangement giving a high amplification ratio (say 1,000 to 1 on the voltage, i.e. 10^6 to 1 on power) the transfer back of a very small proportion of the power from the output end to the input end will be sufficient to render the circuits unstable, or to reduce the amplification very considerably.

It is thus a matter of the very greatest importance to secure an adequate control of the coupling between the low-power and high-power ends of the instrument. This coupling may be capacity coupling, or a mutual inductive coupling, or a combination of the two. Resistance coupling may also be employed in conjunction with either capacity or inductive coupling. Capacity coupling is always present to some extent. At high frequencies it is always important and is generally the controlling factor. If inductive coupling is also used, the condition actually arrived at is a balance between the two.

Fig. 8 shows a method of using a capacity coupling, and Fig. 9 a combination of inductive and capacity coupling. Both these systems are applicable to more

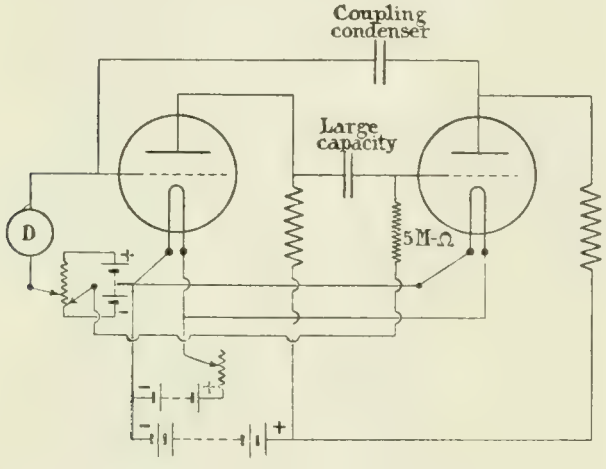

Fig. 8.

than two tubes, but the connections for the capacity coupling must necessarily be made to the right valves or opposition effects will be obtained.

In practice it is desirable that the action of the amplifier should not depend upon a very critical adjustment of this coupling. Consequently the unavoidable coupling must be reduced as far as possible. For high-frequency working, one of the unavoidable sources of this coupling is the capacity between the grids and the anodes of the valves themselves. Formulæ are given in later paragraphs by means of which the results of this coupling can be estimated in any particular case and these results allowed for.

(2) *Control of the tendency towards the generation of oscillations by varying the mean grid voltage.*—A common method of designing an amplifier is to adjust it so that when the mean potential difference between the grid and filament has a particular value there is good amplification with a definite tendency towards the unstable condition. If an adjustment of the grid-filament P.D. is now provided, this tendency can be decreased or increased by making the mean grid-filament P.D. more positive or more negative. When more positive, the grid damping is increased, which increases the effective resistance of the circuits in which the oscillations are produced. Usually, also, the total amplification is somewhat reduced. Both these effects tend towards stability. If the grid is made more negative the conditions are reversed and the tendency to oscillate is accentuated.

(3) *The practical value of "reaction."*—There are two quite distinct ways in which reaction can be employed. In the first place, as has already been pointed out, the tendency to produce self-maintained oscillations enables currents of a given amplitude to be maintained in the input circuit for a smaller power supply from the external source. This is in itself equivalent to amplification. Under perfect conditions, with the reaction under perfect control, it would be possible to secure anything up to an infinite amplification by slowly increasing the power supplied back to the input circuit from the output circuit until the power required from the external source becomes vanishingly small. In practice, however, there are limitations. The control soon becomes very critical and the adjustment so delicate that the least change in the

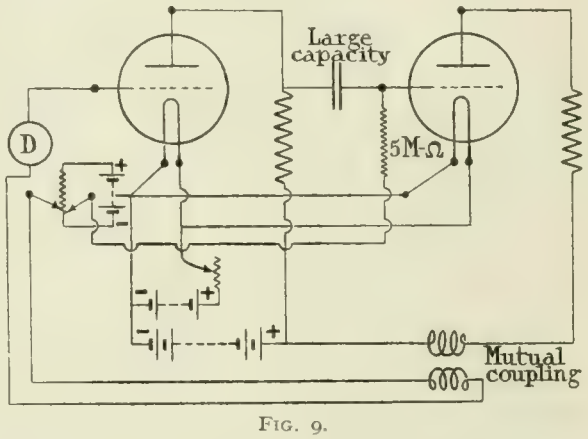

Fig. 9.

conditions in the valves upsets it. Also, unless all the valves are working on points on their characteristics where the amplification is a maximum, any momentary large disturbance will slightly increase the effective amplification and cause the self-maintained oscillations to set in. Thus amplification by "reaction," which in reality is merely using the amplifier to neutralize the resistance of the input circuit, must be reduced to a very moderate amount. The modern tendency is rather in the direction of avoiding it altogether if possible, the extra amplification required being obtained by using more valves in cascade.

In the second place, where continuous waves are being received by the heterodyne method, the use of a separate set of instruments to generate the beating oscillation is avoided if the amplifier can be so controlled as to generate these oscillations itself and yet maintain its power of amplification. Many amplifiers have been designed which serve the double function fairly well, but generally there is considerable loss of amplification and simplicity of operation. The loss of amplification arises from the fact that, once the beating oscillation is started in the input circuit, it immediately builds up to a value which is large compared with the incoming oscillation to be amplified

By the time that this large oscillation has been amplified up by the whole series of valves, the voltage amplitude is such that for the last valves the grid voltage is coursing to and fro far beyond the limits of the slope of the anode-current characteristics. This difficulty is leading under modern conditions to the use of separate low-power generating sets for producing the beating oscillations.

(C) Other Limitations to the Effective Amplification.

(1) *External interference of the same nature as the P.D. variation to be amplified.*—When an amplifier is used for the reception of wireless signals interference is always experienced to a greater or less extent from atmospheric disturbances and from other signalling. These interferences are reduced as far as possible by selective devices. The residuum of the interference is, of course, amplified up with the signal that is being received, and the efficiency of the selective devices determines the extent of the amplification that can be employed effectively. It is obviously useless to attempt to render audible by amplification a signal which is swamped by the interference. The maximum amplification is thus that which brings up to good audibility such interference as cannot be eliminated by any of the selective devices in use.

A discussion of the selective devices is not relevant to this paper.

Somewhat similar limitations are experienced with land line telegraphy from earth currents and magnetic storms.

(2) *Minute irregularities in the behaviour of the valves themselves.*—Small irregularities in the action of the valves are due to two causes, viz. (*a*) the electron emission from the filaments is apparently not perfectly uniform; and (*b*) the amount and nature of the residual gas is not constant.

The result of these small irregularities is to cause small promiscuous changes in the anode currents of the valves near the input end of the amplifier. Each small change is amplified up throughout the whole series and the aggregate gives rise to what are known as the "valve noises."

The "valve noises," again, are not matters for discussion in this paper, although they constitute one of the most formidable obstacles to the attainment of very high amplification.

(3) *Constancy of the batteries used; bad contacts, etc.*—Any irregularity of either the filament heating battery or of the battery supplying the anode current will obviously be a source of trouble. A large capacity across the anode battery is often used to obviate this difficulty if the battery is not above suspicion. Batteries of a large ampere-hour capacity are used for the filaments for the same reason.

Anything of the nature of imperfect contacts must, of course, be scrupulously avoided.

(D) Theoretical Treatment.

(1) *The valve characteristics.*—For a rigorous treatment of the amplifying problems, four characteristics are involved, viz.—

(*a*) Anode current—grid voltage characteristic.
(*b*) Anode current—anode voltage characteristic.
(*c*) Grid current—grid voltage characteristic.
(*d*) Grid current—anode voltage characteristic.

For any adjustment of the mean anode-filament and grid-filament potential differences there will be the corresponding mean anode and grid currents. Any small change made in one potential difference will cause changes in both the currents. For example, if the grid is made more positive to the filament, the anode current will increase and the anode voltage will fall. When the steady conditions are reached, both the anode and the grid currents will have taken up new values corresponding to the new values of the grid and anode voltages.

In general, though by no means always, the current and voltage changes which are to be dealt with in amplifiers are small compared with the voltage range of the active portions of the characteristics. So long as this is the case the characteristics may be regarded as straight lines and the changes of current calculated from the observed slopes of the characteristic curves.

This procedure—which appears to be universal—involves a fundamental assumption, viz. that the ordinary static characteristic is followed even at high frequencies and with minute amplitudes. It is difficult to see why the static and dynamic characteristics should not be the same. The fact remains, however, that it never seems possible to secure the amplification per valve that is indicated by numerical calculations from the static characteristics. That any appreciable time lag can be caused from the time of flight of the electrons is demonstrably impossible with the field strengths that are commonly used. There remain, however, possibilities of changes of surface of filament and, perhaps, also of the grid. With high-power transmitting valves a difference between the static and dynamic characteristic is fairly definitely established and appears to be due to surface changes of the filament. Whether some similar effect takes place in the low-power amplifying valves is a question that requires much further investigation. In the following notes it is tacitly assumed that the static characteristics are followed at all the frequencies contemplated and for all amplitudes, however small they may be.

In making any estimate of the amplification that can be obtained from a valve, and in determining the best circuit arrangement, it is only the slopes of the characteristics at the mean steady potentials that are required. In this paper the following notation is used:—

Anode voltage $= v$.
Grid voltage $= v'$.
Anode current $= i$.
Grid current $= i'$.

$$\frac{di}{dv'} = k_1; \quad \frac{di}{dv} = k_2; \quad \frac{di'}{dv'} = k_3; \quad \frac{di'}{dv} = k_4.$$

The sign convention taken is that v and v' are positive when the anode and grid are positive to the negative end of the filament; and that i and i' are positive when the current is flowing into the valve at the anode and grid respectively (i.e. electrons flowing out of the valve at these electrodes). The slopes are, of course, positive when the current increases with increase of the voltage.

Under normal conditions v is always positive; v' may be positive or negative; i is always positive; i' is always positive in "hard" low-voltage valves, but may be positive

or negative in "soft" valves; $\frac{di}{dv'}$ is positive; $\frac{di}{dv}$ is positive; $\frac{di'}{dv'}$ is positive in "hard" valves but may be positive or negative in "soft" valves; $\frac{di'}{dv}$ is usually negative.

(2) *Theory of the simple resistance circuit.*—The circuit referred to is that of Fig. 1. Suppose that the alternator D superimposes a sinusoidal voltage $\delta v'$ $(= a' + j b'$, j being $\sqrt{-1})$ on the steady grid voltage. Let δv $(= a + j b)$ be the resulting increase of anode voltage. Let δi and $\delta i'$ be the corresponding increases of the grid and anode currents.

Then
$$\delta i = k_1 \delta v' + k_2 \delta v \quad . \quad . \quad . \quad . \quad . \quad (2.1.1)$$
$$\delta i' = k_3 \delta v' + k_4 \delta v \quad . \quad . \quad . \quad . \quad . \quad (2.1.2)$$
$$\delta v = -\delta i \, R_A \quad . \quad . \quad . \quad . \quad . \quad . \quad (2.1.3)$$

Hence
$$\delta v = -\delta v' \frac{k_1}{k_2 + 1/R_A} \quad . \quad . \quad . \quad . \quad (2.2)$$
$$\delta i' = \delta v' \left(k_3 - \frac{k_1 k_4}{k_2 + 1/R_A} \right) \quad . \quad . \quad (2.3)$$

The mean power taken from the alternator is

$$W_D = \text{mean } \delta i' \, \delta v' = \text{mean } \left(k_3 - \frac{k_1 k_4}{k_2 + 1/R_A} \right) (\delta v')^2$$
$$= \left(k_3 - \frac{k_1 k_4}{k_2 + 1/R_A} \right) (\text{R.M.S. grid voltage variation})^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2.4)$$

Inspection of equation (2.2) shows that the two voltages are of opposite phases, and that the ratio of the amplitude is

$$\Psi_1 = \frac{k_1}{k_2 + 1/R_A} \quad . \quad . \quad . \quad . \quad . \quad (2.2.1)$$

where Ψ_1 is the voltage step-up obtainable with one valve. It follows from this equation (2.2.1) that R_A should be given such a value that $1/R_A$ is small compared with k_2. In that case

$$\Psi_1 = k_1/k_2 = m \quad . \quad . \quad . \quad . \quad . \quad (2.2.2)$$

the "grid closeness factor" or "amplification factor" of the tube.

With the tubes commonly used m is of the order of from 5 to 30 and k_2 is of the order of 3×10^{-6} to 30×10^{-6} amperes per volt. Thus if R_A exceeds about 100,000, the full voltage amplification, $\Psi = m$, should be realized when m is in the neighbourhood of 5 and k_2 in the neighbourhood of 30×10^{-6}.

But for valves having lower values of k_2, R_A may have to be increased to 500,000 or even more to obtain this maximum amplification.

This, however, is assuming that the power required can be supplied from the alternator D. This power is given in the preceding equation (2.4). Observing that k_4 is negative, and that with the commonly used hard valves k_3 is positive, the two terms are additive and may represent a serious damping of the input circuit. When $1/R_A$ is small compared with k_2 the power is

$$W_D = (k_3 - k_1 k_4/k_2)(\delta v')^2 = (k_3 - m k_4)(\delta v')^2 \quad . \quad (2.4.1)$$

Of the two terms, k_3 is always much larger than $-m k_4$. Hence the damping of the input circuit is directly controllable by varying k_3. With either "hard" or "soft" tubes this can usually be done by varying the mean grid potential, without at the same time appreciably affecting the k_1 and k_2 slopes. Thus a practically constant voltage step-up can be obtained with a wide range of damping of the input circuit.

(3) *The assumptions involved in the treatment of the simple resistance circuit.*—The conditions assumed in the previous paragraph can never be actually realized, because (*a*) there is a capacity between the grid and the anode of the valve; (*b*) there is some capacity across the resistance R_A; and (*c*) there may be appreciable inductance in the resistance R_A.

With low frequencies (up to, say, 500 cycles per second) and with thoroughly non-inductive resistances the assumed conditions are certainly nearly approached. But with cascade combinations the effects of the grid-anode capacities are noticeable even at frequencies as low as 500 cycles per second.

(4) *The complete case for a single valve.*—The complete case is represented by Fig. 10. The condenser C_A may be merely the stray capacity to earth or it may be a deliberately added capacity. The capacity C′ is the capacity between grid and anode. With good design

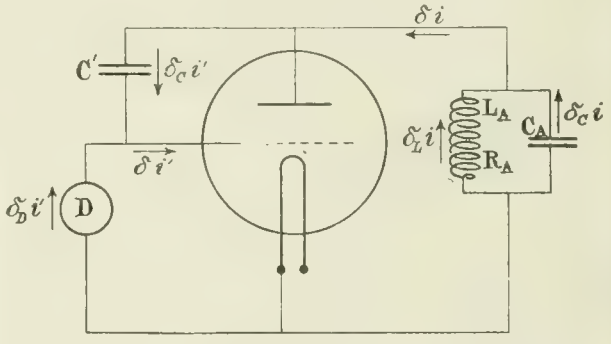

FIG. 10.

this should be confined to the valve only, the contribution from the leads being inappreciable. Under some circumstances, however, it is unavoidable that a proportion of C′ should be due to the relative positions of the input and output circuits.

The amplification for this circuit can be determined on somewhat the same lines as with the simple circuit. Let $\delta_{L} i$ and $\delta_{C} i$ be the two components of the anode current, and let $\delta_{D} i'$ and $\delta_{C} i'$ be the two components of the grid current, the direction of flow being as shown in the arrows in Fig. 10. As before, let $\delta v'$ and δv be the changes of the grid and anode voltage. Then:—

$$\delta_{L} i + \delta_{C} i - \delta_{C} i' = k_1 \delta v' + k_2 \delta v \quad . \quad . \quad . \quad (4.1.1)$$
$$\delta_{C} i' + \delta_{D} i' = k_3 \delta v' + k_4 \delta v \quad . \quad . \quad . \quad . \quad (4.1.2)$$
$$\delta v = -\delta_{L} i \, (R_A + j\omega L_A) = j \frac{1}{\omega C_A} \delta_{C} i \quad . \quad (4.1.3)$$
$$\delta v - \delta v' = -j \frac{1}{\omega C'} \delta_{C} i' \quad . \quad . \quad . \quad . \quad (4.1.4)$$

From (4.1.3) and (4.1.4)

$$\delta_{L} i = -\frac{\delta v}{R_A + j\omega L_A} \quad . \quad . \quad . \quad . \quad (4.1.3.1)$$
$$\delta_{C} i = -j\omega C_A \delta v$$
$$\delta_{C} i' = j\omega C' (\delta v - \delta v') \quad . \quad . \quad . \quad (4.1.4.1)$$

Hence, substituting in (4.1.1)

$$-\frac{\dot{c}v'}{R_A+j\omega L_A} - j\omega C_A(\dot{c}v-\dot{c}v') - j\omega C'(\dot{c}v-\dot{c}v') = k_1\dot{c}v' + k_2\dot{c}v$$

which, being re-arranged, gives

$$\frac{\dot{c}v'}{\dot{c}v} = -\frac{k_1 - j\omega C'}{j\omega(C_A+C') + k_2 + 1/(R_A+j\omega L_A} \quad . \quad (4.2)$$

Writing $y = k_1 - j\omega C' \quad . \quad . \quad . \quad . \quad . \quad (4.2.1)$

and $y_1 = j\omega(C_A+C') + k_2 + 1/(R_A+j\omega L_A \quad . \quad (4.2.2)$

the equation (4.2) becomes

$$\frac{\dot{c}v'}{\dot{c}v} = -\frac{y}{y_1}$$
$$= \phi \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4.3)$$

where $\phi = -y/y_1 \quad . \quad . \quad . \quad . \quad . \quad (4.3.1)$

From (4.1.2) and (4.1.4.1)

$$j\omega C'(\dot{c}v-\dot{c}v') + \dot{c}_{D'} = k_3\dot{c}v' + k_4\dot{c}v$$

which with the help of (4.2) gives

$$\dot{c}_{D'} = \left(k_3 + j\omega C' - \frac{(k_2 - j\omega C')(k_1 - j\omega C')}{j\omega(C_A+C') + k_2 + 1/(R_A+j\omega L_A)}\right)\dot{c}v'$$
$$= k_3 + j\omega C' - y_2 y_3/y_1)\dot{c}v' \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4.4)$$

where $y_3 = k_4 - j\omega C'$.

Equations (4.2) and (4.3) give the voltage step-up to be expected, and equation (4.4) enables the power from the alternator to be calculated.

Various points of interest are obvious from equation (4.2 :—

(*a*) If L_A, C_A and C' are zero the equation is the same as equation (2.2).

(*b*) The cross capacity C' comes in in two ways, viz. (i) It leads to a reduction of the numerator. But k_1 has the largest numerical value of all the slopes and usually the term $-j\omega C'$ is found to be small when numbers are actually applied. (ii) It appears in the denominator where it has an influence on both the resonant frequency and the sharpness of the resonance.

(*c*) If R_A is negligible compared with ωL_A, then (i) There will be resonance when $1/(\omega L\ ) = \omega(C_A + C')$. (ii) The sharpness of this resonance will depend upon the relative values of the terms $1/(\omega L_A)$ and $\omega(C_A + C')$ as compared with k_2. If these terms are small compared with k_2 then the resonance is not marked. This is the prevailing condition in inductively wound amplifiers for medium wireless frequencies, where the capacity C_A is the stray capacity only. If C_A is increased by adding a tuning condenser across the inductance (and of course reducing the inductance correspondingly), then the terms $\omega(C_A + C')$ and $1/(\omega L_A)$ both exceed k_2 and, except at the resonance frequency, are the preponderating terms in the denominator. This means that the resonance is sharp and the amplification is selective. At the point of resonance the voltage step-up is approximately $(k_1 - j\omega C')/k_2$.

(*d*) Rewriting the denominator in the form

$$k_2 + \frac{R_A}{R_A^2+\omega^2 L_A^2} + j\left\{\omega(C_A+C') - \frac{\omega L_A}{R_A^2+\omega^2 L_A^2}\right\}$$

the more exact conditions for resonance are seen to be

$$(C_A + C') = \frac{L_A}{R_A^2 + \omega^2 L_A^2}$$

and under these conditions the maximum voltage step-up is

$$\frac{k_1 - j\omega C}{k_2 + R_A\ R_A^2 + \omega^2 L_A^2}$$

If the term $R_A/(k_A^2 + \omega^2 L_A^2)$ is made decidedly smaller than k_2 the step-up is again $(k_1 - j\omega C')/k_2$.

These general considerations show clearly the conditions to be aimed at in any particular design of amplifier.

A similar general consideration of equation (4.4) is more difficult owing to its greater complexity. Taking the resonant condition, and dealing only with the larger terms the equation is approximately

$$\dot{c}_{D'} = \left\{k_3 + j\omega C'\left(1 + \frac{k_1}{k_2 + \frac{R_A}{R_A^2+\omega^2 L_A^2}}\right)\right\}\dot{c}v'$$

from whence it appears that the effect of the capacity C' is to throw an extra load on to the alternator D. This leads to additional damping of the input circuit, and shows that there will be no tendency to generate oscillations *at the resonant frequency*. At other frequencies, however, this will not necessarily be the case.

The term $-y\,y_3/y_1$ of equation (4.4.) may be written in the form $-\frac{y\,y_3}{a_1 + jb_1}$, where $a_1 = k_2 + \frac{R_A}{R_A^2+\omega^2 L_A^2}$ and

$$b_1 = \omega\ C_A + C' - \frac{\omega L_A}{R_A^2 + \omega^2 L_A}$$

The largest term of the numerator $y\,y_3$ is generally $-j\omega C' k_1$. Neglecting all but this term

$$-\frac{y\,y_3}{a_1 + jb_1} = \frac{j\omega C' k_1}{a_1 + jb_1} = \omega C' k_1 \cdot \frac{b_1}{a_1^2+b_1^2} + j\omega C' k_1 \frac{a_1}{a_1^2+b_1^2}$$

If now the conditions are such that b_1 is negative and large enough for $\omega C' k_1 b_1/(a_1^2 + b_1^2)$ to exceed k_3, then the real part of $\dot{c}_{D'}$ is negative and there will be a tendency to instability. For b_1 to be negative $\omega(C + C')$ must be less than $\omega L_A/(R_A^2 + \omega^2 L_A^2)$. In terms of the reactances, this means that the inductive reactance must be less than the capacity reactance ; i.e. the working frequency must be below the natural frequency of the anode circuit. It is well known that if D is a tuned circuit, the insertion of a small inductance in the anode circuit gives rise to a simple form of oscillating circuit.

The tendency to oscillate can be added to or neutralized by a mutual coupling, M, between the inductance of the grid circuit and the inductance in the anode circuit. For any particular case, the value of M necessary to secure full control of the tendency to oscillate can be estimated as follows :—

Let the tuned circuit consist of an inductance L_G, of resistance R_L, in parallel with a condenser C_G, of resistance R_C. Let I_G be the R.M.S. value of the current in this circuit.

Then $\dot{c}v' = I_G(R_L + j\omega L_G$

or $I_G = \frac{\dot{c}v'}{R_L + j\omega L_G} = \dot{c}v'\left(\frac{R_L}{\omega^2 L_G^2} - j\frac{1}{\omega L_G}\right)$

when R_L^2 is negligible compared with $\omega_s L_G^2$ as is usual and assuming that the power abstracted from the output circuit is relatively small. The induced electromotive force resulting from the mutual coupling is

$$e = \pm j\omega M \, \delta i_{L'} = \mp \phi \cdot \frac{j\omega M}{R_A + j\omega L_A} \cdot \delta v' \quad \text{from (4.1.3.1) and (4.3)} \quad (4.6)$$

which can be written in the form $e = (a + jb)\,\delta v'$.

The power supplied to the circuit by the mutual coupling is the sum of the products of the components of I_G and e that are in phase with one another, i.e.

$$\left(a \cdot \frac{R_L}{\omega^2 L_G^2} + b \cdot \frac{1}{\omega L_G}\right)(\delta v')^2$$

$\delta v'$ in this case being expressed as a R.M.S. value.

The losses in the circuit consist of the heating losses resulting from the current I_G flowing through the resistances R_L and R_C. The power output from the circuit is the component of the current $\delta i'$ in phase with the grid voltage $\delta v'$.

If the conditions are such that the grid-anode capacity leads to a *damping* of the input circuit, this constitutes a further source of power output.

For full control of the oscillations the power supplied through the mutual coupling must exceed the losses plus both these sources of power output.

In the cases in which the grid-anode capacity leads to a supply of energy *to* the grid circuit, then the mutual inductance can be reduced correspondingly.

It thus follows that in an amplifier that is to be used over a considerable range of frequency, it is necessary to provide for a wide variation of the mutual M. Usually the mutual is arranged to give both positive and negative values up to a maximum of, say, 50 per cent more than is required under the worst conditions. It is very desirable that the maximum value of the mutual should not be unnecessarily large. If this is the case the adjustments for those conditions requiring small values of M become altogether too critical.

(5) *Two valves in cascade.*—The calculation of the amplification depends upon the method of linking together the valves. The circuits of Figs. 4, 5, or 6 reduce to the general case of that shown in Fig. 11, where all batteries, etc., are omitted, as only the alternating components of the currents and voltages are required.

With step-up transformers between the valves, the conditions are rather different, but can be approximated to by taking the grid voltage of one valve as ρ times the anode voltage of the previous one, where ρ is the ratio of the turns of the transformer. The grid currents will be $1/\rho$ times the corresponding anode currents. The effect of the cross capacity is, however, very complex, and it is doubtful whether any useful purpose is gained by working out the conditions in detail on these inaccurate assumptions. With a transformer of 1/1 ratio with large capacity between the grid and anode windings the circuit of Fig. 11 is applicable. The inductance L_A will be the equivalent inductance of the inductance of the two transformer windings in parallel, due allowance being made for the mutual inductance. The circuit of Fig. 7 can also, therefore, be represented by the circuit of Fig. 11.

When dealing with more than one valve, it is assumed

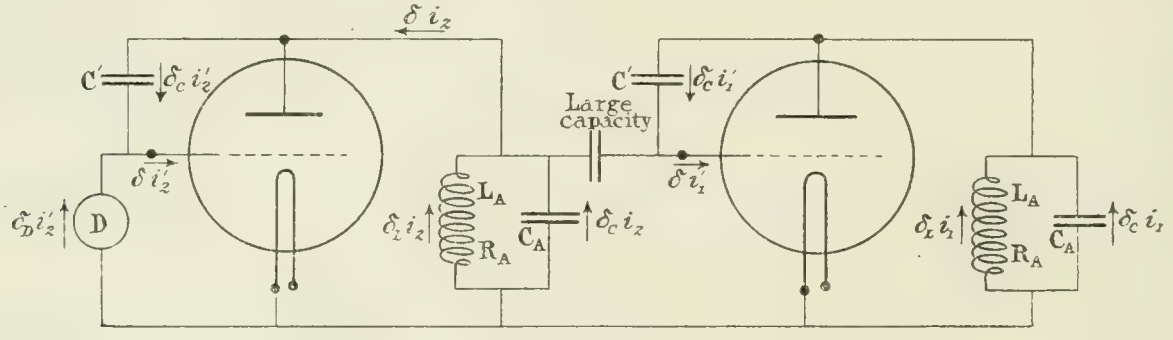

FIG. 11.

that the valve characteristics are identical and that the circuits are identical. This is very approximately the case in practice.

A small modification of the notation is necessary when dealing with multiple valves.

Prescript letters have already been used to indicate the path of the currents. Subscript numbers will now be introduced to indicate the particular valve of the series referred to. The valves are numbered from the *output end towards the input* end. The application of this notation to the two-valve case is shown in Fig. 11.

The equations for the first valve are almost identical with those for the single valve given in the previous paragraph, viz.

$$\delta i_{L'_1} + \delta i_{C_1} - \delta i_{C'_1} = k_1 \delta i'_1 + k_2 \delta v_1 \quad . \quad . \quad (5.1.1)$$

$$\delta v_1 = -\delta i_{L'_1}(R_A + j\omega L_A) = j\frac{1}{\omega C_A}\delta i_{C_1} \quad . \quad (5.1.3)$$

$$\delta v_1 - \delta v'_1 = -j\frac{1}{\omega C'}\delta i_{C'_1} \quad . \quad . \quad . \quad (5.1.4)$$

Whence

$$-\delta v_1\left\{j\omega(C_A + C') + k_2 + 1/(R_A + j\omega L_A)\right\} = \delta v'_1(k_1 - j\omega C') \quad . \quad (5.2)$$

Writing, as before :—

$$y = k_1 - j\omega C'$$
$$y_2 = j\omega (C_A + C') + k_2 + 1/(R_A + j\omega L_A)$$

and making these substitutions,

$$-y_1 \delta v_1 = y \delta v_1'$$

or
$$\delta v_2 = \phi_1 \delta v_1' \quad \ldots\ldots\ldots \quad (5.4)$$

where
$$\phi_1 = -y/y_2 \quad \ldots\ldots\ldots \quad (5.4.1)$$

The value of ϕ_1 is the amplification for the one valve expressed in unreal quantities. The actual voltage step-up, Ψ, will be found from ϕ_1 in the usual way by converting to the form $\phi_1 = a + jb$ and determining the value of $(a^2 + b^2)$.

For the second valve, the equations can be written down in the same way :—

$$\delta L_2' + \delta C_{L_2} + \delta C_{g_1} - \delta i_1 - \delta C_{g_2} = k_1 \delta v_2' + k_2 \delta v_2 \quad (5.5.1)$$

$$\delta i_2 = -\delta L_{L_2}/(R_A + j\omega L_A) = j\frac{1}{\omega C_A} \delta C_{L_2} \quad (5.5.3)$$

$$\delta v_2 - \delta i_2' = -j\frac{1}{\omega C'} \delta C_{L_2} \quad \ldots \quad (5.5.4)$$

$$\delta i_2' = k_3 \delta v_2' + k_4 \delta v_2 \quad \ldots\ldots \quad (5.5.5)$$

Substituting for the currents in terms of the voltages

$$-\delta v_2 (y_2 + j\omega C' + k_3) - \delta v_2' (k_4 - j\omega C') = y \delta v_2' \quad (5.6.1)$$

Writing
$$y_2 = y_2 + j\omega C' + k_3 \quad \ldots\ldots \quad (5.6.1.1)$$

and as before
$$y_1 = k_2 - j\omega C' \quad \ldots\ldots \quad (5.6.1.2)$$

then
$$-y_2 \delta v_2 - y_1 \delta v_2' = y \delta v_2' \quad \ldots \quad (5.6.2)$$

But $\delta v_2 = \delta v_2'$, whence from (5.4)

$$-y_2 - y_1 \phi_1) \delta v_2' = y \delta v_2'$$

or
$$\delta v_2 = \phi_2 \delta v' \quad \ldots\ldots\ldots \quad (5.7)$$

where
$$\phi_2 = -\frac{y}{y_2 - y_1 \phi_1} \quad \ldots\ldots \quad (5.7.1)$$

The current from the input circuit is

$$\delta D_2' = \delta i_2' - \delta C'$$
$$= k_3 \delta v_2' + k_4 \delta v_2 - j\omega C' (\delta v_2 - \delta v_2') \quad \text{from (5.5.4)}$$
$$= (\ldots - y_1 \delta v_2' + y \delta v_2' \quad \text{from (5.6.1) and (5.6.1.2)}$$
$$= (\ldots - y_1 + y \phi_1 \phi_2) \delta v_2' \quad \text{from (5.4) and (5.7)} \quad (5.8)$$

The real part of this current represents power output from the input circuit. When the real part is positive this represents additional damping. If the real part is negative, a tendency to oscillate is indicated.

Writing $\delta D_2' = a + jb\ \delta v_2$, then the mean power taken by the amplifier from the input circuit is mean $a(\delta v_2')^2$. If the grid circuit consists of an inductance and condenser in parallel, as in the previous paragraph, the mean power expenditure is $I_G^2 (R_L + R_C)$.

But $I_G = \omega C_G (\delta v_2')$ approximately, $\delta v_2'$ being here expressed in R.M.S. values. The power expenditure is therefore $\omega^2 C_G^2 (R_L + R_C) (\delta v_2')^2$. The power required from external sources is therefore

$$\left\{\omega^2 C_G^2 (R_L + R_C) + a\right\} (\delta v_2')^2$$

If this is negative the combination of circuit and amplifier will be unstable and oscillations will be generated.

(6) *General considerations of the equations of the previous paragraph.*—It is obvious that the same general considerations as those given in paragraph (4) are applicable, but that the precise conditions are even more involved.

Neglecting $j\omega C'$ in comparison with k_1, equation (5.7.1) becomes

$$\phi_2 = \frac{k_1^2}{k_1 (j\omega C' - k_2) + y_1 y_2} \quad \ldots \quad (6.1)$$

If tuned anode circuits are used, C′ is very small compared with C_A, and R_A is small compared with ωL_A. Under these conditions, when the circuits are tuned so that $\omega L_A = 1/(\omega C_A)$, $y_1 y_2 = k_2 (k_2 + k_3)$.

$$\phi_2 = \frac{k_1^2}{k_1 (j\omega C' - k_4) + k_2 (k_2 + k_3)} \quad \ldots \quad (6.1.2)$$

and if negative mean grid potential is used so that k_3 and k_4 are negligible

$$\phi_2 = \frac{k_1^2}{k_2^2 + j\omega C k_1} \quad \ldots\ldots \quad (6.1.3)$$

This equation (6.1.3) shows that the grid anode capacity is deleterious and reduces the step-up per valve under the particular tuning conditions assumed. The capacity contributes, however, to the reaction, and under some circumstances the contribution to the reaction may more than neutralize the loss of step-up per valve.

The condition that $\omega L_A = 1/\omega C_A$ is not necessarily the best condition. Still neglecting R_A and C′ compared with ωL_A and C_A respectively, the denominator of (6.1) becomes

$$k_2 (k_2 + k_3) - \left(\omega C_A - \frac{1}{\omega L_A}\right)^2 - k_1 k_4$$
$$+ j\left\{(2k_2 + k_3)\left(\omega C_A - \frac{1}{\omega L_A}\right) + \omega C' k_1\right\}$$

The minimum value of this denominator is very nearly that corresponding to

$$(2k_2 + k_3)\left(\omega C_A - \frac{1}{\omega L_A}\right) + \omega C' k_1 = 0$$

or
$$\omega C_A - \frac{1}{\omega L_A} = -\frac{\omega C' k_1}{2k_2 + k_3}$$

Under these conditions

$$\phi_2 = \frac{k_1^2}{k_2 (k_2 + k_3) - k_1 k_4 - (\omega C' k_1)^2/(2k_2 + k_3)}$$

If negative grid potential is used so that $k_3 \ll k_2$ and $k_1 k_4 \ll k_2^2$, then with this tuning

$$\phi_2 = \frac{k_1^2}{k_2^2 - m^2 \cdot \frac{1}{4}\omega^2 C'^2}$$

and the capacity C′ leads to an improvement in the amplification.

In the case of circuits in which C_A is of the same order as C′ and both R_A and L_A are large it is impracticable to make any generalizations, as all the terms become of importance. Numerical cases may, however, be worked out and they very quickly give an indication of the results to be expected or of the modifications that are necessary to attain any desired results.

Equation (5.8) for the current from the input circuit is even more difficult to interpret generally. It is available, however, for numerical calculations.

(7) *Three valves in cascade.*—The treatment of the first two valves is exactly as in paragraph (5). For the third valve, equations can be written down identical with those of (5.5), but with each subscript number increased by one. From these an equation

$$-y_2\,\delta v_3 - y_3\,\delta v_2 = y\,\delta v' \quad . \quad . \quad . \quad (7.6.2)$$

is derived which is exactly similar to (5.6.2).

Then substituting

$$\delta v_3 = \delta v_2 = \delta v_1/\phi_2 \text{ from (5.7)}$$

and

$$\delta v_2 = \delta v'_2 = \delta v_1/\phi_1 \text{ from (5.4)}$$

$$\delta v_1 = -\frac{y}{y_3/\phi_1\phi_2 + y_2/\phi_2}\,\delta v'_3 = \phi_3\,\delta v_3 \quad . \quad (7.7)$$

where

$$\phi_3 = -\frac{y}{y_3/\phi_1 + y_2/\phi_2} \quad . \quad . \quad . \quad . \quad (7.7.1)$$

Similarly,

$$\delta i'_{D3} = (y_2 - y_1)\,\delta v'_3 + y_3\,\delta v'_2$$
$$= (y_2 - y_1 + y_3\phi_3\phi_2)\,\delta v'_3 \quad . \quad . \quad . \quad (7.8)$$

(8) *The general case.*—Corresponding to equations (5.6.2) and (7.6.2) there is obviously a general equation

$$-y_2\,\delta v_n - y_3\,\delta v'_{n-1} = y\,\delta v'_n \quad . \quad . \quad (8.6.2)$$

The substitutions to be made are $\delta v_n = \delta v'_{n-1} = \delta v_1/\phi_{n-1}$ from a general equation corresponding to (5.7); and $\delta v_{n-1} = \delta v'_{n-2} = \delta v_1/\phi_{n-2}$ from a general equation corresponding to (5.4).

With these substitutions

$$\delta v_1 = -\frac{y}{y_3/\phi_{n-2} + y_2/\phi_{n-1}}\,\delta v'_n = \phi_n\,\delta v'_n \quad . \quad (8.7)$$

where

$$\phi_n = -\frac{y}{y_3/\phi_{n-2} + y_2/\phi_{n-1}} \quad . \quad . \quad . \quad (8.7.1)$$

Similarly

$$\delta i'_{Dn} = (y_2 - y_1)\,\delta v'_n + y_3\,\delta v'_{n-1}$$
$$= (y_2 - y_1 + y_3\phi_n\phi_{n-1})\,\delta v'_n$$

(9) *The capacities and inductances required for a given control of the reaction.*—The usual methods of securing control are either by mutual inductance between the input circuit and one of the anode circuits of the series or by a variable capacity between one of the anodes and the grid of the input valve.

The couplings are usually small, and as an approximation it is assumed that the power fed back to the input end from the valves at the output end is negligible compared with the power available there. In this case the method used in deriving equation (4.6) can be employed for more than one valve. If the coupling is from the first valve to the input grid, then

$$e'_n = \pm j\omega M \cdot \delta i'_{L1}$$
$$= \mp \frac{j\omega M \cdot \phi_n}{R_A + j\omega L_A}\,\delta v'_n \quad . \quad . \quad . \quad . \quad . \quad (9.4)$$

More generally, if the coupling is to the anode circuit of the *m*th valve,

$$e'_n = \pm j\omega M\,\delta i'_{Lm} = \mp \frac{j\omega M\,\phi_m/\phi_{m-1}}{R_A + j\omega L_A} \cdot \delta v'_n \quad . \quad (9.4.1)$$

The capacity coupling can be treated on similar lines if it is assumed that the capacity of the coupling condenser is so small that the current passing through it is negligible compared with the current at the anode of the valve to which the capacity is connected.

If the capacity K is connected to the *m*th valve anode, there will be a voltage $(\delta v_m - \delta v'_n)$ across it. Consequently a current $\delta i'_{nK} = j\omega K\,(\delta v_m - \delta v'_n)$ flows into the grid side of the input circuit, and the current $\delta i'_{Dn}$ required from the input circuit is reduced by a corresponding amount. Considering the power, it is only the real parts of these two currents that are involved. If the real part of $\delta i'_{nK}$ is positive, it follows that a smaller positive real part is required from $\delta i'_{Dn}$. If no positive real part is required from $\delta i'_{Dn}$, then the circuit is just unstable and on the verge of generating oscillations.

As above,

$$\delta i'_{nK} = j\omega K\,(\delta v_m - \delta v'_n)$$
$$= j\omega K\,(\phi_m/\phi_{m-1})\,\delta v'_n \quad . \quad . \quad . \quad (9.5)$$

whence the current can be calculated for any desired arrangement, and by a process of trial and error a suitable value of K can be determined.

Discussion.

Professor G. W. O. Howe: It is, of course, quite unavoidable that there are many details of a subject like this which cannot be dealt with in the limited scope of a paper, but I confess that I felt a little disappointed at the number of things which, to judge from its title, I expected to find in the paper and which the author has not even mentioned, such as the relative advantages of air-core and iron-core transformers for connecting one valve to the next, both for telephonic frequencies and also for radio frequencies, the use of multi-layer coils, and the effect of capacity between the layers of the coils. I suggest that a better title for the paper would be "The Theory of Multi-stage Amplifiers," rather than "The Design of Multi-stage Amplifiers." Design should not be undertaken until one has mastered the theory, and it should then deal with the special points arising in the application of the theory to the actual construction; the present paper is mainly an elaboration—and a very able elaboration—of the theory of the multi-stage amplifier. The author gives a reference at the foot of the first column on page 65 to a paper by Latour in 1916. I think it is only fair to add that

last July Latour read a much fuller paper on "The Theory of Amplifiers" before the Société Française des Electriciens which will be found in the July number of the "Bulletin." He does not, however, go into the theory with anything like the thoroughness shown by the author in this paper. Latour does not consider such things as the capacity between the plate and the grid, but his paper is nevertheless very interesting and should be read in conjunction with the present paper. The methods followed are different and the formulæ look very different, but this is partly because Professor Fortescue expresses the characteristics of the valves in terms of conductances, whereas Latour employs resistances. The four constants k_1, k_2, k_3, and k_4, are in Latour's paper four different resistances, if we agree to call these differential ratios resistances. I might mention in this connection that Latour gives reciprocals of these four constants for the standard French valves. He gives $1/k_1$ as 2,000 to 3,000 ohms; $1/k_2$ as 15,000 to 20,000 ohms; $1/k_3$ as 250,000 to 400,000 ohms, and $1/k_4$ as 50 megohms to 100 megohms. I should like in the next place to refer to Fig. 4. This figure is, I know, merely diagrammatic and is not intended to represent an actual amplifier, but it should be pointed out that the voltage drop across the resistance R_A in the plate circuit of the first valve is much larger than should be applied to the grid of the second valve, and it might be necessary to introduce a very large grid battery in the second valve in order to keep the potential difference of the grid down to the proper value. Latour points out in his paper that this drawback can be avoided by dividing the anode battery of the first valve into two parts, inserting one part where the author has it and placing the second part with R_A between the tappings to the grid of the second valve. In this way the voltage drop in R_A can be made equal to the voltage rise in the latter part of the battery, so that no steady voltage is applied between filament and grid. The statement on page 69 that "with high-power transmitting valves, a difference between the static and dynamic characteristic is fairly definitely established, and appears to be due to surface changes of the filament" is a very important point if one finds that the amplications predicted from considerations of the slopes of the characteristics are not obtained in practice. In thinking over possible explanations of this, it occurred to me that it may be due to the fact that the action of the valve is very sensitive to changes in filament temperature. When one is taking a static characteristic curve the temperature of the filament for each reading does not depend entirely on the heating current flowing through the filament, but is affected to some extent by the current through the valve from the filament to the anode. So that when plotting a static characteristic curve, although the current through the filament may be kept constant, it is possible that in changing from point to point we may cause very slight modifications in the temperature of the filament. When the current in the filament is oscillating at a high frequency the temperature of the filament has not time to follow those oscillations on account of the thermal capacity of the filament; it is oscillating then with a fixed temperature of filament. That may be one of the causes of the discrepancy between the amplification predicted from the static characteristic and the amplifications actually obtained at high frequencies.

Mr. L. B. Turner: In the very interesting paper before us, equations have been evolved governing the action of any number of similar triodes in cascade. We must appreciate the skill with which the author has marshalled the equations in the endeavour to give to the mathematical results some apprehensible physical significance; but I think many will feel that here, as so often, the unwieldiness of the mathematical results must drive the designer to rely mainly on experiment, guided of course by a few elementary conceptions which are probably best derived from consideration of the simple case of a single triode. I should like to draw attention to one such guiding principle not explicitly developed in the paper. As the paper

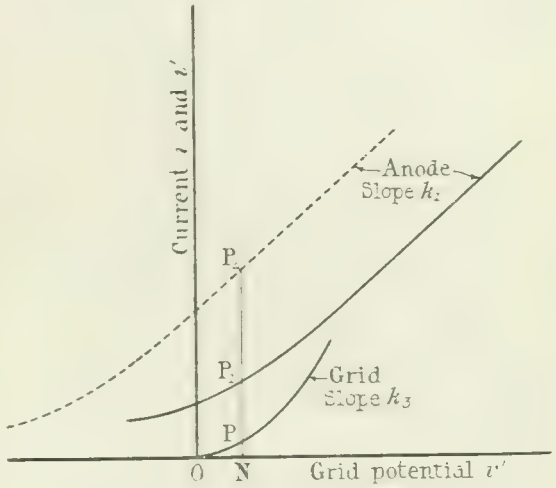

FIG. A. Avoidance of backlash.

points out, the tendency of an extra-strong signal, or an over-shoot in the adjustment of the controlling reactions, to set up self-maintained oscillation, is a great difficulty to the designer. "Unless all the valves," says the author, "are working on points on their characteristics where the amplification is a maximum, any momentary large disturbance will slightly increase the effective amplification and cause self-maintained oscillation to set in." All who have attempted to construct sensitive amplifiers suitable for unskilled manipulation well know this difficulty. It manifests itself as backlash in the adjustments around the threshold of oscillation. It is the phenomenon cultivated and used in the oscillatory valve relay, which I described before the Institution last June. This action is, I think, to be avoided in the following way. Take the case of the full-line curves in Fig. A herewith, where O N represents the working mean grid potential. Any increase of v' will increase the slope k_1, which, it may easily happen, will overpower the accompanying increase in k_3, and so give the "valve relay" effect we wish to avoid. If now, by raising the mean anode potential, or modifying the dimensions of the triode,

we change our anode point to P_2 on the dotted curve, where k_1 is sensibly independent of v', a rise of v' only serves to increase the damping, i.e. to inhibit oscillation. And since k_3 is increased by a rise of v' more than it is decreased by an equal fall v', the larger the amplitude of alternating E.M.F. applied to the grid the less ready is the system to oscillate. A defect in the design of many amplifiers, I think, has been the neglect to ensure that the representative point on the anode curve shall be well off the concave foot of the curve P_1 and well on the almost straight portion P_2. The second point I should like to dwell on for a moment is the tendency, approved by the author, to resort to many triodes rather than utilize the sensitivity to be got from retro-action towards the self-oscillating condition. If it were possible to construct a multi-triode amplifier without any retro-action, it is obvious that no fine adjustments would be required. The small inconstancies in the triodes, to which the author refers, would then only slightly increase or decrease the amplification obtained. But, as the paper points out,

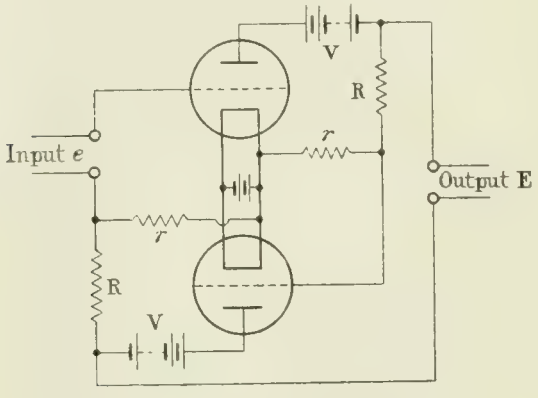

FIG. B.—Kallirotron circuits.

in high-frequency work at least we cannot avoid retro-action. It is inherent in the triodes and their circuits, and we are obliged to counter it by controlled retro-action in the opposite sense. Now there is no practical difficulty in arranging for adjustment of coupling or grid potential or the like, however fine. The difficulty is not in finely controlling the reaction; it lies in the inconstancies of the triodes and, possibly, the batteries. It seems to me questionable, therefore, whether the resort to many triodes, with their retro-action and counter retro-action, is the best course. Should we not rather attempt a close approach to the infinite sensitivity that one or two quite constant triodes could give us? I have worked on these lines in an aperiodic retro-active arrangement, a description of which will be published shortly, and which is illustrated typically in Fig. B. Here a rise of the upper grid potential (produced, for example, by the signal e) produces a rise of upper anode current, which, owing to the ohmic drop in r, produces a fall of lower grid potential; this in turn produces a fall of lower anode current and hence a rise of upper grid potential. If this last change of potential is nearly as great as the original change e, the latter is more or less completely self-sustaining. The effect, looked at otherwise, is as though the resistances of the anode circuits had been more or less completely wiped out; so that small changes e produce large changes in the anode currents, and therefore large changes E. Amplifications E/e up to 2,000 can be obtained and maintained; and this with circuits giving a theoretical maximum amplification without retro-action of only about 3 per triode. Further, in this symmetrical arrangement, changes in each triode are accompanied by equal and opposite changes in the other triode; and the process of adjusting the circuits brings about the desired condition of decreasing amplification with increasing signal, so that there is stability with any signal strength. In conclusion I wish to suggest that the mathematical analysis in the paper would be most instructively applied to the design of some concrete amplifier, or to the analysis of some amplifier which has actually been constructed, and I hope that the author or someone else will carry out and publish this work.

Mr. J. K. Catterson-Smith: About two years ago, when we were experimenting with amplifiers at Portsmouth and elsewhere, the results obtained frequently indicated a much smaller magnification than was expected from consideration of the characteristics of the valves used. The author shows by his investigations that this is to be attributed to stray capacity in

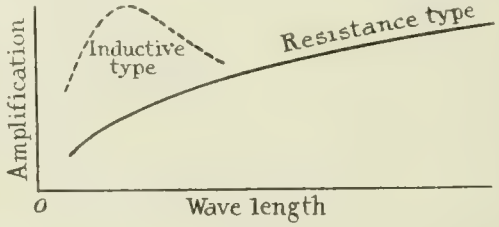

FIG. C.

the circuit which has a marked effect in resistance couplings at the higher frequencies. The ordinary type of expression which appears under the heading of "Theory of the simple resistance circuit" on page 70 was found to be of little use in the design of multi-valve amplifiers, because it was soon observed that the amplification of a resistance-coupled circuit varied considerably with the wave-length of the signal being received. It was only by the application of the theoretical investigations of the author, which are embodied in this paper, that corroboration was obtained of the form of the amplification curve when plotted against the wave-length. The amplification obtained with resistance-coupled multi-valve circuits rises as the wave-length increases (i.e. as the frequency decreases), as shown by the full line in Fig. C herewith. In the simple form of the expression used on page 70 there are no terms dependent upon wave-length and it is necessary to employ the expressions given by the author in order that due allowance may be made for the wave-length or frequency, because of the so-called self-capacity or stray capacity of the various leads and the other parts of the apparatus. I think the fact that the author's work was available immediately

for helping to clear up those difficulties and pointing the way for improvement in the design of inductive coupling and indicating the limitations of the resistance-type coupling was, at any rate to most of us, a sufficient demonstration of the utility of his work. I do not know whether, in view of what was said by Professor Howe, I ought to speak about some of the more practical sides of the question with which I was mainly concerned. Reading such a paper as this after listening to the previous papers read before the Institution, members must, I think, be impressed by the fact that there seem to be so many simple ways of obtaining amplification, and yet it is curious no one particular method is standardized as superior to all others. The reason is that at present each different type of amplifier has its particular field of usefulness. The resistance type of amplifier, if it is built properly, is extremely useful, more or less because of the extremely wide wave-length. The inductive types are inclined to suffer in their total magnifications if the curve is opened out by any alteration to the circuit. If I may refer to the resistance amplifier in particular, I might say that the first difficulty met with was in the production of a resistance (R_A in the paper) without much capacity, and which will not itself vary at any time during its operation, because any slight variation in the resistance is liable to affect the final highly-magnified signals. We experienced difficulty at once when we attempted to make these resistances. We naturally ran quickly through all the ordinary forms of graphite lines, Chinese ink on paper, metal lines drawn on glass and burnished with an agate so as to weld the metal. All these forms proved unsatisfactory, and at the author's suggestion I carried out an investigation of the possibility of constructing resistances using the fairly well-known method of making a platinum film by using colloidal platinum such as is used in the production of ordinary lustre-ware. We achieved a good deal of success with that method, and eventually we were able to produce resistances up to 100,000 ohms with small glass plates or on porcelain tubes not exceeding 4 inches in length and $\frac{5}{8}$ inch in diameter. At the same time, these resistances could carry without deteriorating or losing their efficiency a much larger current than was actually used by the triodes for reception. There were difficulties connected with the production of these platinum resistances, and other investigators working in the same field produced alternative forms of resistances which were satisfactory, notably the resistance composed of carbonized cellulose made by Mr. Mullard. That resistance has been highly satisfactory for "grid leaks," and we also found it satisfactory for resistance-coupling anode currents. As it is limited to rather a small current, if one wants to deal with a large current the platinum form of resistance is often more satisfactory for high frequencies. There is one other thing I should like to mention which was referred to by Professor Howe, namely, the possibility of using iron-core high-frequency transformers—I have not seen much work done in that direction. We had a few iron-core high-frequency transformers, but as they did not give very satisfactory results they were discarded in favour of air-core transformers.

Captain H. J. Round: I should like to mention the question of very high amplification and valve noises. I have carried out one or two experiments in that direction. I noted quite early that the valves produced in America were very much more silent than the English valves, the American valves having oxide-coated filaments. Secondly I noted that the valve noises due to the filament were tremendously decreased by using sharply tuned amplifier transformers, particularly with short wave-lengths, in so much that with wave-lengths of 200 metres, which were available to us during the war, I was able to get a satisfactory amplification of voltage of half-a-million high frequency, practically without any valve noises. The tuning curves were extremely sharp, and the result was produced by 22 valves in cascade. It was quite a satisfactory piece of apparatus for the operators to use; in fact they used it for many weeks without an engineer being present. The fact that valve noises are decreased by shortening the wave-length seems to indicate that the pulses producing the noises have more energy in the long waves than in the short waves. The fact also that sharp tuning of the amplifier coupling transformers decreased the noises, indicates that their energy is distributed over wide ranges of wave-length. I think that, with care in design, the author's estimate of 1,000 voltage amplification is very much on the low side, but it is certainly a very practical value in robust amplifiers.

Squadron Leader J. Erskine-Murray, R.A.F.: I think the paper will be of real assistance to designers, as it is practical and covers the fnndamental part of the subject very well indeed. As Professor Howe has pointed out, however, it leaves many real difficulties untouched; such things as stray capacities, valve noises, and the difference between the static and kinetic characteristics. I think there is no doubt of the existence of this difference, indeed we in the Air Force have made a long series of experiments on it. The principal result obtained is that in a power valve, working under certain inefficient conditions, the current calculated from the static characteristic is 20 per cent less than that observed. By taking a phase difference other than 180° between grid and anode voltages in the static characteristic one gets an apparent increase of current, but, unfortunately for this explanation, the efficiency thus calculated disagrees badly with that observed. It looks as if there might be, during the idle portion of the cycle, i.e. the half-cycle when the grid is most negative, some collection of electrons between the filament and the grid, partially due, perhaps, to momentary rise in temperature of the outer surface of the filament. Thus the emission during the idle half-cycle may provide electrons which are suddenly drawn off as the voltage begins to rise. This suggestion of course requires experimental test, but it is not improbable that the action may be like that described by Dr. H. S. Sand, in the case of an electrolytic cell in which one gets a temporary burst of current immediately on applying the voltage.

Captain J. A. Slee, R.N.: In view of the rather curious experience I have had during the war in handling amplifiers, there are two practical points of some interest which I should like to mention in connection with valve noises. One is that the difficulty met with in practice is not always the fault of the valve itself but of the

supply at high tension. In the old days, when one was dependent upon dry batteries, the behaviour of those batteries themselves was peculiar, and a great many bad amplifier noises were traced to these large batteries of dry cells. We found by experience that the matter was made very much worse by soldering the strips of these dry cells together to make connection. The heat worked along the metal tabs and in some way decomposed the surrounding electrolyte, the result being noises which were, I suppose, electrolytic. From a practical point of view the result was appalling. There is another very great difficulty, although one is at a loss to put any highly scientific value to it, due to the fact that the circuits frequently would not give us the amplification which we expected. As far as one was able to trace that back, it was due to an absorption of energy in the surrounding metal bodies, probably bad instrument construction, and was largely overcome by later practice. It was essential to avoid capacity to earth in the instrument and in all leads going to it. A third point has cropped up in the practical handling of amplifiers, namely, that in the general nature of amplifiers everything depends so much upon the particular service for which they are to be used. If we could rely upon the presence of highly skilled operators, or else on the quintessence of perfect workmanship in the manufacture of amplifiers, we could make use of one or two valves with resonance circuits reacting upon one another to a greater or less extent so as to bring the valves up to the verge of sustained oscillation but not over it. Working in that way enormous amplification could be obtained with a small number of valves. In the small amount of experience which I have had, it was easier to handle the shorter waves in that way. Again, when we came to the condition of using transformer-coupled valves, there was one point which appeared to be of enormous importance, namely, the ratio of the step-up of the transformer between the valves. Setting that aside for the moment, the transformer amplifier gave us comparatively flat tuning from a selective point of view, but, all the same, tuning was present unless a large resistance was included in the transformer windings. In any case, in practice one was always face to face with the choice between using the remaining part of one's wireless circuit to give selectivity when using transformer or resistance amplifiers, or of not relying upon the rest of one's receiving circuit for selectivity but using the extraordinarily sharp peak of maximum amplification which can be obtained at the point of resonance in an amplifier whose circuits were tuneable. Amplifiers which are of the greatest possible service for one particular class of work might, and often were, found to be unsuitable for others, either because the selectivity was absent or because the adjustment of the completed instrument was too difficult. It seems, as a practical result, that there is room for the three types of amplifier, quite separate from one another. Although it has never been my fortune to have to make such amplifiers myself, I believe that one of the outstanding difficulties of the simplest-looking form, that is the resistance amplifier, is to get steady resistances. The greatest difficulty in making a satisfactory transformer amplifier is to get wire which, when wound to a sufficiently high inductance and resistance, will not be too bulky. The great difficulty with the tuned type is to arrange any mechanical means which will obviate the necessity of individual tuning of every one of the circuits. When we have one valve in a resonance amplifier, there are, roughly speaking, three adjustments to be made. We have to tune the grid circuit and the anode circuit exactly to the required wave and to adjust the retro-action. If we use two valves we have to duplicate that performance, and when we get a slight discrepancy between the tuning of the circuits attached to the first and second valves we run the risk of getting both of them oscillating on frequencies which are nearly the same and thus get beats of audible frequency. The result is that for anyone who is not thoroughly accustomed to handling these circuits, it is extremely difficult and most disheartening for the operator, unless he can keep watch on a fixed wave-length, when he can leave the adjustment alone. In the old days of soft valves it was almost one man's work to drive the valve, and another man's work to read the signal. We were then working with ordinary operators having little education, and it was an exceedingly difficult business; but that is rather ancient history. I have pointed out one or two of the differences between theory and the practical application of these amplifiers from the point of view of those who have to handle operators who are by no means scientifically minded or scientifically trained. It should always be borne in mind that the circuits and details of any amplifier must depend to a great extent on the characteristics of the valves to be used. Circuits which will suit one type of valve may be quite unsuitable for valves of another type.

Mr. B. S. Gossling: In writing what may well prove to be a classical paper for the subjects considered, the author has, I think, rather disarmed criticism by so carefully defining the scope which he intended his paper to cover, and again by the thoroughness with which he has included all the electro-dynamic components which are really essential to the action of the circuit for the main purpose of amplifying. There is a most important point, viz. whether the statical and dynamical characteristics of the valve can be treated as the same. The amount of discrepancy which used to be found between the calculated and the observed amplifications on multiple-valve amplifiers was such that it was necessary to suppose a very considerable difference, we will say 30 or 40 per cent, between the statically observed characteristic of the valve, with which I was most concerned myself, and the characteristics which one would expect to be there in order to account for the observed amplifications. On page 69 the author puts forward the suggestion that this discrepancy may be due to surface changes in the filament, in the same way, apparently, as a similar phenomenon which has been mentioned by Squadron Leader Erskine-Murray in connection with the power valves. The manner in which this was put incited me to make a small calculation dealing with this point, as to what the rapidity of the most obvious type of surface change was likely to be, namely, the type of surface change which is apparently responsible for the difference between

the static and the dynamical characteristic in the power valve. In one of the earliest published works on high-vacuum apparatus Langmuir showed very clearly that small traces of gas in the valve can very appreciably depress the total current which can be extracted from the filament if sufficiently strong fields are applied. If the statical characteristics of high-power valves which are not exhausted to an extremely high degree are not taken very rapidly, this effect leads to a false estimate of the height to which the characteristic curve rises, and in many cases that accounts for an apparent discrepancy between the amount of power delivered by the valve when it is oscillating and the amount of power which one would expect from characteristics which have had to be measured comparatively slowly. One would think that that kind of effect might appear in the smaller valves. The action, as explained by Langmuir, is that the positive ions derived from the residual gas impinge on the surface of the filament and there form a layer, not necessarily more than a molecule thick, which seriously alters the conditions of electron emission from the filament. When we come to consider how it would work in this case, the simple calculation which I propose to give shows that it is quite unlikely that the tentative explanation which he gives is the true one. In the ordinary receiving valve the number of positive ions present is comparatively small. Suppose we take a numerical case, and let it be that of a receiving valve in which the current of positive ions coming back and impinging on the filament amounts to one-sixth of a micro-ampere (many will realize that that is a rather large estimate of the stream of positive ions likely to be coming back); suppose also that the area of the filament is one-hundredth of a square centimetre. The number of molecules required to cover that filament with a single layer would be one-hundredth of 10^{16}, that is 10^{14}; the number of positive ions required to make up one-sixth of a micro-ampere is 10^{12}. The ratio of the number of molecules required to the rate at which molecules are being supplied tells us at once that the time required to coat the filament with only one layer of molecules would be 100 seconds. That is a surprisingly long time, but it does agree very well indeed with the slow rate of variation of the current which one observes on first switching on a fresh valve in order to take its statical characteristics. It also shows very clearly that this particular cause cannot be called upon to explain any regular cyclical variation having a frequency of thousands or hundreds of thousands per second. Smaller changes in the characteristics, changes of a fraction per cent such as one would require to assume in order to account for valve noises, are not covered by the calculation at all. It is very likely that one particular part of the area of the filament may be more responsible for the form of the characteristic than another, and a change in this area may produce a sudden minute change in the characteristic, which would give one a noisy valve. A great deal has been said about the subject of valve noises. I think the most definite thing which has been established with regard to valve noises is that they depend in very large measure on the temperature of the filament. The higher the temperature of the filament, whatever its composition, the greater is its tendency to make a noise; and it is rather unfortunate that the valves which were most used during the war were standardized to work at a filament temperature which is just over the noise-point for the ordinary tungsten usually employed in electric lamps. It is an example of the way standardization ties one to a particularly difficult piece of apparatus where a fuller knowledge at the time of the original design would have entirely avoided the difficulty. In that connection I am a little inclined to take exception to Professor Howe's remarks about the title of the paper. I take it that what the author had in mind in selecting that title must have been the deliberate design of multiple-stage amplifiers basing the design on a connected theory, rather than an empirical design based on general experience. In conclusion I should like to say that a compact and readily-comprehensible summary of the mode of action of so complicated an instrument as the multiple-valve amplifier, involving, as it does, a very large number of variables, is extremely useful to those who happen to be concerned with the design of valves which are to be used for these amplifiers. The valve itself unfortunately involves a very large number of variables, and unless the corresponding variables on the circuit side can be reduced to manageable formulæ, effective collaboration between the people concerned with the valves and those occupied with the circuits becomes practically impossible, and it also becomes practically impossible to hope that anyone will arise who is likely to be capable of developing both valve and circuit at the same time. I think Captain Round has gone further in that direction than anybody, but I am inclined to think that the complications now arising in the subject may very likely prove to be beyond even his power.

Mr. J. Scott-Taggart: Although the author has described a number of cases of valves used in cascade for amplification purposes, yet no mention has been made in the paper, or in the discussion, of several forms of retro-active coupling of great value in multi-stage amplifiers. The methods described in the paper consist in employing magnetic couplings or capacitative couplings between the plate of the last valve and the grid of the first. Retro-active amplification may be obtained not only by coupling the plate of the last valve to the grid of the first, but by making suitable connections between any of the intermediate valves. The condition for retro-active amplification is that when the potential of the plate increases, that of the grid of the preceding valve chosen should also be rising, and vice versa. If a condenser is now connected across the plate and grid, retro-action is obtained, and if the condenser is of sufficient capacity, self-oscillation is set up. In a resistance amplifier, the sign of the plates changes at each valve. Consequently, retro-action would be obtained by connecting the last plate to the first grid of an amplifier possessing two, four, six, eight or, in short, an even number of valves. If an odd number of valves were used, absorption—the opposite to amplification—would take place, and the greater the capacity the less would be the amplification and the less the tendency to oscillate. In general,

we can say that retro-active amplification is obtained when the coupling condenser connects the plate and grid of valves adjacent to each other or separated by an even number of valves. Obviously, the greater the number of valves in between, the more critical is the adjustment of the coupling condenser, which then requires to be of very small dimensions. Owing to the difficulty of ensuring regular working, it is desirable to arrange the coupling between the plate of one valve and the plate of a previous valve in the series. The retro-action is now weaker and allows of a more gradual adjustment. The coupling condenser should now be connected across any two plates which are undergoing potential changes of the same sign, as, for example, the first and third, third and fifth, first and seventh, and so on. In the paper no mention is made of the retro-action obtainable by connecting a high resistance of the order of 10 megohms across the plate of one valve and the grid of a previous valve, or the plate of one valve and the plate of another. In this case the resistance takes the same place as the coupling condenser, and it would be interesting to have mathematical data regarding the retro-active effect of a given resistance under these conditions. Another form of retro-active coupling not mentioned consists in connecting the filament side of the grid circuit of, say, the initial valve to a suitable point on the resistance included in the plate circuit of one of the subsequent valves. The calculation of the retro-action (producing amplification or absorption) is in this case quite straightforward. The question of self-oscillation in multi-stage amplifiers has been raised. This, of course, may be accomplished by employing one or other of the various means of obtaining retro-active absorption. Another method which has its uses consists in connecting a large capacity in series with a high resistance across the input oscillatory circuit. This method is especially applicable when iron-core low-frequency amplifiers are used for long-wave reception and when such amplifiers tend to oscillate of their own accord. A damping arrangement of this nature might be applied to many different amplifier circuits if placed across any circuit liable to oscillate continuously. Although not coming within the scope of the paper, amplifier noises have received considerable attention in the discussion. It has not, however, been pointed out that these noises occur chiefly in those amplifiers which employ a form of inter-valve coupling which passes on low-frequency current variations. Valve noises are of low frequency, and consequently an amplifier which only passes on the high-frequency variations of plate current will work more quietly than a low-frequency amplifier or high-frequency amplifier capable of being used as a low-frequency amplifier. Amplifiers employing iron-core transformers (which are usually used for low-frequency amplification although Latour has also used them for high frequencies) are usually the most noisy. High-frequency amplifiers employing air-core transformers are naturally more silent. Any irregularities of plate current in the first valve will not be induced to any appreciable extent into the grid circuit of the second valve, and this will be especially the case if the coupling between the plate and grid oscillatory circuits is loose. Resistance amplifiers, if well designed, are silent. This is the case when the resistance amplifier is intended to magnify only the high-frequency current. If the grid and filament of a valve in a series is connected across the high resistance in the plate circuit of the preceding valve, not only will high-frequency oscillations be passed on but also any valve noises due to variations in the electronic plate current of the first valve. In order to filter out these low-frequency variations, a stopping condenser of very small capacity may be inserted between grid and resistance. Being of small capacity this condenser, besides insulating the grid from the voltage drop across the resistance, will offer a high reactance to low-frequency variations while allowing oscillating electromotive forces to be impressed on the grid. When separated plate and filament batteries are used another condenser may be connected between the resistance and the filament. Besides making the amplifier more silent, the stopping condenser prevents any rectified pulses produced in the earlier valves from being amplified, only the high-frequency components being passed on. Such amplifiers possess the property of amplifying weak signals to a greater extent than strong signals. It may be added that most of the work on resistance amplifiers has apparently been carried out by Brillouin and Beauvais.

Dr. W. H. Eccles: I will take the opportunity to emphasize a point which one of the previous speakers referred to. Such calculations as those in the paper are valid whenever one has a definite frequency to deal with. Lest anyone should think that in wireless practice, for instance the case of the note magnifier discussed by the author, the method is not applicable, I would remind them that when signals are being received between fixed stations, especially where one would propose to use amplifiers, say between Rome and Annapolis, the note is either fixed as a spark note or is adjustable as a heterodyne note, and therefore the analysis is quite valid for the audio frequencies of wireless telegraphy. It would not apply so well to the use of amplifiers for picking up miscellaneous frequencies such as sounds under water or sounds in the air, but in the places where the author applies it to wireless telegraph problems in general the analysis is in my opinion a trustworthy solution. My first experience of an amplifier was with a three-stage audion amplifier, supplied by Dr. de Forest before the war. It enabled one to pick up signals in the middle of the Pacific from very great distances in all directions. That experience opened my eyes to the possibilities of the amplifier, and when I got home I tried to make one, and met many of the difficulties mentioned in the paper, which although mainly a theoretical one abounds with numerous practical hints, although they are not all explicitly stated. For instance, the capacity between the anode and the grid is dealt with, and also the retro-action between parts of the circuit by accidental capacity or accidental mutual inductance between leads. The author mentions things like the necessity for good contacts, good batteries, steady voltages, and miscellaneous things of that kind. Anyone who tries to make an amplifier will come up against these points

and will be grateful to the author. In conclusion we are able to congratulate ourselves that we have seen something of what the Silent Navy has been doing during the past few years as regards amplifiers. Doubtless a great deal of this paper has been used in design work in the Admiralty during these years.

Professor E. W. Marchant (*communicated*): There are one or two points in connection with this paper about which I should like to have further information. On page 66, when dealing with the damping of the anode circuit of the valve amplifier, the assumption is made that the damping resistance is made up of two parts: (*a*) resistance of the circuit, and (*b*) the equivalent resistance due to the resistance of the tube in parallel with the circuit. It is a little difficult to see what is the justification for the assumption that the oscillating circuit simply consists of the condenser C_a, and self-induction L_a, with the tube in parallel with it. The anode circuit and battery are to be regarded as the source of the oscillations which are produced in the resonant circuit; and if this is the case, the anode path, i.e. the path from the anode to the filament, is in series with the battery, and presumably the total resistance of the circuit will have to be the sum of the resistance of the tube, the resistance of the battery (which is usually shunted by a large condenser), and the equivalent resistance of the oscillating circuit. It would, I think, be enlightening to have a further explanation of the sentence, that the "latter component decreases with a decrease in the ratio of L_a/C_a and vice versa." If L_a is large, then it is clear that the effective resistance of this circuit will be relatively greater, and if this is so, the effect of the resistance of the anode path in series with it should be relatively smaller. This view of the matter results in the same conclusion, as that stated by the author, viz. "That a circuit having a very high ratio of L_a/C_a is inefficient in an amplifier," but this is due to the relatively high effective resistance of the oscillating circuit, i.e. $(L_a\omega/R_a)$ is a large quantity in such a circuit. On page 72 there is, I think, a misprint; if the transformer has a voltage ratio of ρ the current ratio will be $1/\rho$ and not ρ^2. On page 73 also at the foot of the first column, the mean power supplied by the amplifier should be $a\,(\delta v_2')$ and not $a\,(\delta v_2')^2$. I hope the author will be able to give some information as to the practical improvements that have been effected by the design of valve circuits in accordance with the methods which he has set forth. Most people have not had the good fortune to deal experimentally with valves very much during the last year or so, and it would be interesting if he could give some information on the results he has obtained.

Professor C. L. Fortescue (*in reply, communicated*): With regard to Professor Howe's initial criticism, the variety of the points raised during the discussion is in itself a sufficient answer. In one single paper it is not possible to deal with all aspects of such a complex subject. The author unfortunately had not seen Latour's latest paper, and the circumstances under which he proposes to neglect the grid-anode capacity in the valve were therefore unknown to him. As pointed out in the paper, the cross capacity is of the greatest importance under almost all conditions of operation, and to neglect it means that all notice of retroaction is being omitted. Professor Howe's suggested explanation of the possible difference between the static and high-frequency characteristics seems hardly sufficient to explain the loss of amplification sometimes observed. In the valves commonly used for amplifying, the watts expended in the filament are in the neighbourhood of 3. The additional watts, due either to the bombardment by positive ions or to the emission current passing along the filament, are probably less than 1 per cent of this amount. Moreover, the valves are usually working below the saturation point where considerable changes of the filament current cause very little change in the amplification.

Squadron Leader Erskine-Murray and Mr. Gossling also discussed this question. The effect observed in the transmitting valves is well explained by the contamination of the surface of the filament. But, as Mr. Gossling pointed out, this effect is quite inadequate to explain any high-frequency effect. The fact that the valves are working below saturation is in itself almost sufficient to rule it out. This is a problem requiring further investigation. It may be that it is not the valve that is at fault. The errors may lie in the method of measuring the amplification or in the methods of measuring the capacities in the valve. But against the latter theory is the fact that with the inductance amplifiers depending upon the valve capacities for resonance, the observed resonance points agree with the calculations. Possibly the explanation is to be found external to the valves or circuits as suggested by Captain Slee.

With regard to Mr. Turner's remark that the mathematical treatment is so cumbrous that resort is usually made to practical trial, it should be borne in mind that a little arithmetic may be cheaper than making up several trial instruments. And not only that, actual calculation generally brings out the relative importance of the various factors with more certainty than practical trial of complete instruments. The point raised by the same speaker that amplification should always take place at the best possible adjustment of grid voltage is extremely important and is very often overlooked. It is largely a matter of valve design, the ideal amplifying valve being one having a short straight part of the anode characteristic occurring at the same grid voltage as the first quick increase in the slope of the grid curve. Such a valve would be stable and would amplify small signals more than large ones. Mr. Turner advocates amplification by reaction, i.e. by means equivalent to introducing negative resistance into the input circuit. It is the author's experience that to obtain high amplification in this way always leads to unduly critical adjustments. It is interesting to hear that the resistance coupled "Kallirotron" is an improvement in this respect. This may possibly be due to the resistances having a steadying effect on the valve.

Mr. Catterson-Smith has spoken of the curves of amplification obtained with the various types of amplifiers. It is of interest to note that the pure resistance amplifier can be given a certain amount of selectivity by using very small grid coupling capacities in the early stages, as pointed out by Mr. Scott-Taggart.

It is believed that one of the objects of the designers in giving the well-known French amplifiers this property was to reduce the valve noises. The author regrets that he cannot agree with Mr. Scott-Taggart that the resistance amplifiers are always quiet. In many cases they have been very noisy indeed. To some extent the coupling resistances were to blame and Mr. Catterson-Smith's remarks on the difficulties that were experienced in constructing satisfactory resistances of very small self-capacity are of interest. Captain Slee drew attention to the fact that in the early days the noises were frequently due to defective batteries. With the modern amplifiers having large capacities across the high-voltage supply, this source of trouble is practically eliminated. The author has seen an amplifier working in which the high-tension battery could be disconnected and yet the signals came in quite well for at least 10 seconds. But in spite of this the valve and other noises were still present.

The question of valve noises was also discussed by Captain Round, who said that with short waves and tuned circuits he had had no great difficulty. This no doubt is due to the fact that at the relatively low frequency of the valve noises the impedances of the circuits he was using were quite small; in other words, his amplifier was a very bad one at the low frequency. Mr. Gossling, also discussing valve noises, remarked that there was a clearly defined temperature at which they set in. It is undoubtedly a fact that for a given amplification the lower the temperature of the filament the less are the noises. But it is the author's experience that the noises always set in just as the emission becomes free, and he concludes from this that the source of the noises has something in common with the source of the emission. The American valves having coated filaments and working at much lower temperatures are much less noisy, as mentioned by Captain Round. But the noises are not entirely absent in spite of the low filament temperature. Again, short filaments of which the central portions are very hot are notoriously noisy, which suggests that the irregularities may depend principally on the electron emission per square millimetre. The American valves have long filaments and therefore a low intrinsic emission. It is the author's opinion that the further development of the high-power amplifier is principally dependent on the elimination of these noises, and careful trials of the low-temperature coated filament should undoubtedly be carried out.

Mr. Scott-Taggart mentioned many different ways of obtaining retro-action and of connecting the anode circuit of the one valve to the grid of the next. It does not appear that any definite rules can be laid down that will cover all the various types of amplifiers in use. With untuned amplifiers a well-designed capacity coupling generally gives good results. But with tuned circuits either capacity or magnetic coupling appears to be equally good. In general, the more complicated arrangements which are only suitable for a particular frequency should be avoided. The author has had no experience of the resistance coupling between grid and anode for retro-action. With regard to the grid connections, it is usually preferable to use those arrangements giving circuits of the lowest impedance at the low frequency of the valve noises.

With regard to Dr. Eccles' remarks on the applicability of the mathematical treatment to the case of noises where the impulses are not in the form of sine waves, this depends upon the decrement of the inter-valve circuits. For a resistance or heavily damped inductance amplifier the results are applicable practically as they stand. For a tuned amplifier the results, as pointed out in the paper, obviously only apply for relatively undamped impulses.

Professor Marchant raises the question of the action of the valve as a resistance across the R_A, L_A, C_A circuit of Fig. 3. Any change in the voltage across the anode circuit causes a corresponding change in the anode current quite independently of changes in the grid voltage, with the result that the valve may be looked upon as a resistance of numerical value:—

(Change of anode voltage) ÷ (Change of anode current)

connected in parallel with the anode circuit. This naturally leads to an increase in the damping as the ratio L_A/C_A is increased, irrespective of the actual resistance of the inductance itself. It may be observed that with inductances of a given design the ratio R_A/L_A is constant. The damping of the circuit from this source will therefore be constant. As to the practical application, this was very generously dealt with by Mr. Catterson-Smith, to whom the author is indebted for a large part of the experimental basis on which the mathematical treatment rests.

CARBON ARCS FOR SEARCHLIGHTS.

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(From the National Physical Laboratory.)

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1. *Synopsis.*—This paper describes a series of experiments undertaken at the request of the Admiralty (D.T.M. Dept.) and is published by permission. Their object was:—

(*a*) To develop the best method of testing carbons in order to prove their value for searchlights.
(*b*) To compare the relative qualities of existing carbons, other than flame carbons, for producing high-intensity searchlight beams.
(*c*) To determine what improvement can be made either in the carbons themselves or in the methods of burning them.

It was at first proposed to make measurements of illumination at different parts of a searchlight beam under actual working conditions in the open, but the sources of error encountered were so great as to cause this method to be abandoned in favour of an indoor method of test, at any rate for the first series of experiments.

In the Laboratory the carbons were burned in an integrating photometer of cubical form, and simultaneous measurements were made of the average candle-power given by the arc and of the surface brightness of the positive crater. The apparatus is fully described in the body of the paper and illustrated diagrammatically in Fig. 1.

By this method a comparison was made of 13 different types of carbons, both those already in use in the British and French Services, and others specially prepared by the General Electric Company. Experiments were made with two devices having for their object the control of the arc and its maintenance in a central part of the crater to ensure even burning of the carbons.

One of these was an electromagnetic device, while the other depended upon a slow rotation of the positive carbon. For high current densities (0·3 ampere per sq. mm. and over) it was necessary to copper both positive and negative carbons. It was found that while change of potential difference on the arc produced no definite detectable change of candle-power, an increase in arc length beyond a certain value produced a decrease both of crater brilliancy and of candle-power. It seems likely that if allowance is made for the light obscured by the negative carbon, the shortening of the arc will be found to produce an increased average candle-power even at short arc lengths, but the exact amount of the obscuration is difficult to determine with accuracy, as is shown in section 19 of the paper.

In general it seems to be clearly established that for any one carbon the candle-power increases linearly with the current, while the crater brightness also shows a real increase, though its magnitude is not sufficient to determine the form of the relationship in this case.

For the types of carbon considered, and apart from smoothness of running, there seems to be no definite difference of any magnitude either in average candle-power or crater brightness for carbons of the same diameter run at the same current. The efficiency in candle-power per ampere increases, however, for the same current density as the diameter of the positive carbon is increased.

1. Methods of Test.

2. *Open air measurements.*—When the investigation was started it was expected that large differences would be found in the light yielded by the various carbons, and it was proposed to burn them in a searchlight in the open, measuring the intensity of the resulting beam. It was realized that varying atmospheric conditions and differences in the carbons themselves would be disturbing factors, but it was hoped that with careful arrangements for estimating the atmospheric scattering of the light and by taking the average of a large number of readings, these factors would become inappreciable compared with the differences in the light emitted by the carbons themselves. Searchlights were therefore set up, and an 800-yard horizontal course was arranged from the Laboratory across Bushey Park. The measuring station at the other end of the course was fixed, and the projector in use was turned through the necessary angles. These were measured by means of a telescope fixed to the case and sighted on to a distant scale. Arrangements were also made so that an image of the arc was projected on to a screen, and thus it was possible accurately to fix the position of the positive crater with reference to the projector mirror.

For measuring the loss of light due to atmospheric scattering, an Ediswan tungsten arc (Pointolite) lamp was used in the focus of a second searchlight mirror and the beam projected along the course to a photometer 300 yards away. The other side of the photometer received a second beam of the same light which had been reflected by optically ground mirrors

so that it travelled through a length of the atmosphere some $2\frac{1}{2}$ times as long as the direct beam. It was expected by comparing the intensities of these two beams to obtain a sufficiently accurate estimate of the atmospheric condition to enable corrections to be applied to the illumination measurements. It was found, however, that the actual differences of beam intensity yielded by the different carbons (other than special flame carbons) were relatively small, and that the various sources of uncertainty in the conditions were sufficient to mask such differences completely.

3. *Sources of uncertainty of measurements in the open.*—Before passing to the alternative method of procedure it is desirable to discuss some of the difficulties met with in measurements out of doors.

(*a*) *Scattering of light by particles of moisture.*—Very often the atmosphere in the daytime is exceedingly clear, giving promise of a fine night for measurements, but shortly after dark the illumination in a searchlight beam is found to be falling. When this is first noticed the atmosphere, to ordinary observation, does not appear to be very different, but when the illumination has fallen by some 25 per cent the scattering of the light becomes noticeable. Two nights both adjudged to be clear have been found to yield differences in illumination of more than 25 per cent. Over the course in Bushey Park a still night in fine weather never remains clear sufficiently long for a proper series of measurements. The atmosphere is also patchy; at one moment it may be reasonably clear and at another a local cloud of haze may drift over one section of the course. This may readily be seen in misty weather, but the same condition must exist in a lesser degree when the haze is too attenuated to be observed. This accounts for the appreciable up and down variations in brilliancy which were sometimes noticed in the course of a set of readings lasting for, say, 30 minutes.

Probably a clear breezy night gives the best promise of good atmospheric conditions, but a breeze often drops when darkness sets in and bad conditions again prevail.

(*b*) *Draughts in the searchlight.*—Broken weather with considerable wind, if not actually rainy, causes a bad condition of draught in the searchlight and irregular burning of the carbons.

(*c*) *Position of positive carbon in relation to the mirror.*—When the arc is burning well there is little difficulty in ensuring that the position of the crater is correct in relation to the mirror, but any slight burning away on one side makes this uncertain and causes the distribution of illumination over the beam to change.

(*d*) *Variations in the carbons themselves.*—A given type of carbon does not yield uniform results, nor does one carbon over its whole length. Differences may amount to as much as 35 per cent. It is necessary to obtain the average behaviour of a large number of carbons of any one type before a conclusion can be drawn as to relative merits.

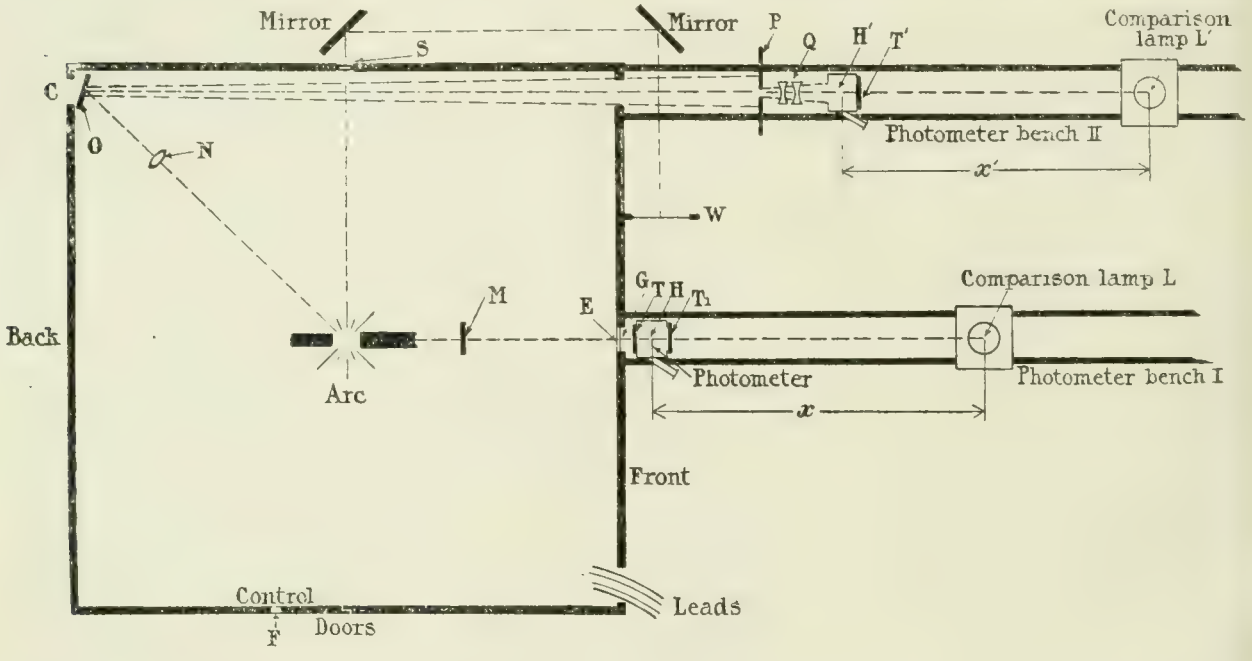


FIG. 1.—Diagram of apparatus, etc.

(*e*) *Mirror.*—Results, to be comparable, must clearly be made with the same mirror and apart from it are not likely to have any absolute value.

(*f*) *Measuring apparatus.*—Measuring apparatus, which is necessarily of a portable character for searchlight tests in the open, must be regarded as liable to an uncertainty of at least $\pm$ 5 per cent.

If it were not for atmospheric scattering of the light, the other variables might be eliminated by taking the average of a large number of readings, but the infrequent occurrence of suitable conditions for testing makes this virtually impossible in this climate.

All results of measurements in the open should therefore be subject to very careful scrutiny to see that the above sources of error are negligible compared with the differences of brightness which are being looked for.

4. *Laboratory measurements.*—In the Laboratory method of test which was adopted in place of tests in the open air with projectors, the carbons were examined alone without any mirror. Two quantities have mainly to be considered :—

(i) The total flux of light emitted by the carbons alone.

(ii) The intrinsic brightness of the positive crater.

Of these the second is the more important for present purposes, since it is a measure of the intensity in the beam of the projector; for, if the brightness of the crater of one carbon is greater than that of another, the beam will be correspondingly brighter. If, therefore, crater brightness can be accurately measured we have a direct criterion of the ability of the carbon to yield a high intensity beam, provided the searchlight is adjusted to give a beam of minimum divergence. If, however, a beam of given divergence is obtained, the intensity will be directly proportional to the total flux of light given by the positive crater whatever its size or brightness. For this purpose, therefore, the more important factor is the total flux emitted towards the mirror, or, what may be taken as proportional to it for ordinary carbons, the average candle-power of the crater in directions embraced by the mirror. It is shown later that for a given current an increase in intrinsic brightness is produced by an increase in current density. Hence it follows that improvements in ordinary searchlight carbons are mainly obtained by reducing the diameter of the positives if the current is to be kept at the same value. This seems to be true for all carbons which depend for their light upon the incandescence of the crater surface. The total flux for a given current also increases with the current density but apparently at a lower rate than the crater brightness.

There is a class of flame carbons such as those used in the Beck, Harrison, or Sperry lamps to which this general statement does not apply. These carbons mainly depend on the light emitted by vapour in the arc and close to the positive; these carbons are not considered here.

It is, of course, obvious that a quantity which it would be useful to measure in addition to the total flux is the flux emitted within the solid angle embraced by the mirror. The light received by the mirror (together with that obscured by the negative carbon) represents some 70 per cent of the total light emitted from the positive crater—if this radiates as a true diffusing surface, i.e. as if it were a disc emitting the same total quantity of light as the crater from one of its faces. The proportion of the whole light which actually reaches a given mirror, therefore, depends only on the symmetry of burning of the carbon and the extent of obscuration of the negative carbon. For ordinary purposes it may probably be safely assumed that measurement of total flux bears a very constant ratio to that received by the mirror so long as the crater has not burned unsymmetrically, i.e. in such a way that it shows its incandescent surface when viewed at right angles to the axis of the carbon. There is also the small proportion of the light due to the incandescent tip of the negative and the luminosity of the arc itself, to be taken into account; but the difficulties of making measurements of the light emitted within a given solid angle have resulted in the decision to postpone this and to base the preliminary results given in this paper on the measurements of total flux, which are more readily obtained. It is intended, however, in due course to extend the methods of measurement here described to the investigation of the amount of light emitted within certain solid angles.

5. *General description of apparatus.*

(*a*) *Measurement of total flux.*—The principle of the integrating globe photometer has been employed, but, following a suggestion by Dr. W. E. Sumpner * that, to a fairly close approximation, a whitened cube would give as good results as a sphere, this form of integrator has been adopted for the purposes of the present investigation. A cube has great advantages for projector lamp work in that it has a flat floor upon which the lamp can be supported, and it can have doors at the side permitting easy access for adjustment and examination of the lamp. Further, it is much more easy to construct than a sphere, particularly in the large sizes required for projector arc lamps whose average candle-power is of the order of 30,000 candles. It is necessary, however, to choose for the calibration of the cube a standard lamp which has approximately the same distribution of light as the lamp to be tested.

(*b*) *Detailed description of parts of apparatus.*—(i) The integrating cube used in the present investigation has 8 cubic metres' capacity (2 metres side) and is illustrated in sectional plan, Fig. 1. The arc lamp is entirely controlled from outside the cube. Two images, in directions at right angles to each other and to the axis of the carbons, are projected through the walls of the cube permitting examination of the arc while burning. The electrical measuring instruments, feeding and locating arrangements, and electromagnetic control (when in use) are manipulated from outside, so that there is no necessity to open the cube except to change carbons. Ventilation is provided by means of adjustable shutters at the sides and top. Readings are taken simultaneously of crater brilliancy and candle-power. The brilliancy is measured by projecting a magnified image of the front of the crater along a photometer bench. By the use of a negative lens placed where the image comes to a focus, any small part of the crater image can be isolated and the intensity at this point determined.

The cube is constructed of wood and is mounted on castors. It has doors the full height and width of one side. It is covered inside with asbestos or uralite, and cleaned off so that all inside surfaces are flush and smooth. The roof has a series of sliding shutters 1 ft. wide, so that any required opening can be used. It also has a series of shutters which work horizontally along the centre of the front of the cube, one of which carries the small translucent window E. A similar

* *Illuminating Engineer* (London). 1910, vol. 3, p. 323.

series of shutters is recommended for ventilation adjustment in the back wall of the cube.

All the inside surfaces are treated with three coats finished with gelatine and zinc white. It is advisable as far as possible to whiten also any objects which have to be in the cube—for instance, cables, lamp-stand, base, etc.

(ii) The diffusing window E. This consists of two plates of special colourless glass, each plate being ground with carborundum powder on both surfaces, and fixed so that the inside face is flush with the surface of the cube wall. Close to the window at G is fixed an iris diaphragm with about 70 mm. opening, permitting adjustment of the illumination on the photometer to a value which will enable the standard lamp to work on a convenient part of the photometer bench. Once fixed, however, the diaphragm opening must not be changed in the course of an experiment or of a calibration, nor must the distance of the photometer head from the window be varied since the distance between the window and the photometer in these experiments is small, and the illumination at the photometer is therefore not strictly proportional either to the area of the window or to the inverse square of the distance.

(iii) Photometers H, H′, and Photometer Benches. These are Lummer-Brodhun photometers of the usual contrast type, and ordinary photometer benches about 3 metres long.

(iv) Neutral light filter T. In order to reduce the illumination at the photometer when the arc lamp is burning, a neutral-tinted gelatine filter, T, is placed between the window and the photometer. The transmission value, t, of this filter must be known accurately, as it is removed and another substituted during the calibration of the cube. The transmission coefficients therefore become multiplying factors for the candle-power (see par. 6, "Calibration").

(v) Colour filter T_1. A bluish filter is inserted between the photometer and the comparison lamp to render the colour of the light from the latter similar to that from the cube when the arc lamp is in use. The transmission coefficient, t_1, of this filter has also to be determined once for all, so that the filter can be removed during the daily calibration of the cube.

(vi) Comparison lamps L, L′. These are ordinary-vacuum tungsten-filament lamps operating at about 0·68 candle per watt, mounted on movable carriages, which work along the photometer tracks.

(vii) Screen M. The opaque disc M is about 10 cm. diameter, and is placed in the direct line between the arc lamp and the window E and approximately midway between them. No direct light from the source must fall on the window, which only receives light from the inside walls of the cube. During calibration the screen M is moved, if necessary, so as to come between the standard lamp and the window.

(viii) Lens N. The lens N projects an image of the front of the crater (after reflection from the mirror O) through an opening in the cube, on to the white screen P. An ordinary spectacle-trial-case lens 14·3 mm. diameter and 1·5 diopters is used.

(ix) Mirror O. This is a plain back-silvered 4 in. diameter mirror mounted so that it can be tilted or turned about a vertical axis. The operator obtains access to the adjustments through the opening C and thus regulates the position of the arc image on the screen P.

(x) Screen P and lens Q. The screen is a white matt celluloid sheet 3 mm. thick and about 20 cm. square, fixed to a frame which carries the lens Q. P, Q, and the photometer H′ are mounted together in such a manner that their mutual positions cannot change. They are also rigidly attached to the photometer track. The screen P has in it a circular aperture of 10 mm. diameter, bevelled off to a sharp edge. The lens system Q consists of two negative lenses of 16 and 20 diopters. It must be mounted so that the centres of H, Q, and the aperture in P, are accurately aligned on the axis of the beam from the mirror O.

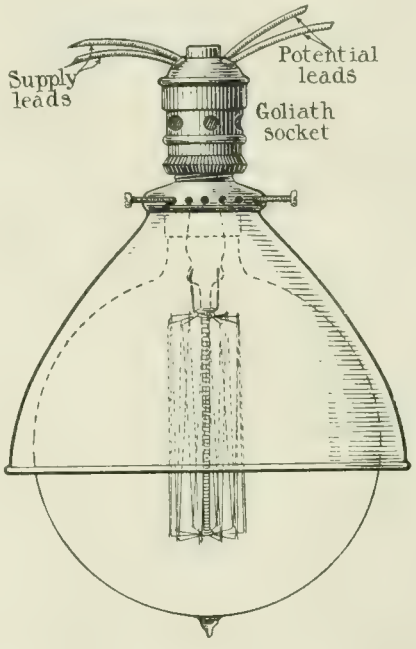


FIG. 2.—Standardized lamp and hood, having similar light distribution to the arc lamp used in calibration of the integrating cube.

The lamp is rated at 240 volts, 1,000 watts.
Average candle-power at 240 volts = 422 candles.

(xi) Colour filter T′. This is another bluish colour filter having a similar function to that of T_1.

(xii) The optical system. This comprises the crater, the lens N, the mirror O, and the screen P, and has the following dimensions:—

Crater to N	828 mm.
N to P	3,440 mm.

The important dimension is the distance from N to the screen P on which the image of the crater is focused.

(xiii) Lens S. The lens S casts an image of the arc, viewed from the side, on to the translucent screen W via the two mirrors shown.

6. *Calibration for measurement of total flux.*—The cube has to be calibrated in absolute measure for candle-

power, and the other optical system for crater brightness in candles per sq. mm. The combined constant of the cube and photometric apparatus is determined by burning in the cube a lamp of known average candle-power (*m.s.c.p.*). If the integrator were spherical it should theoretically give accurate results, however much the distribution of the light from the standard differed from that of the test lamp. The gear inside the cube, however, and particularly the bulky arc lamp and its support, render this assumption dangerous and a standard source of light should be selected which has approximately the same light distribution as the test lamp.

The standard lamp used for calibration of the cube is shown in Fig. 2; it is a large 240-volt 1,000-watt vacuum-type lamp made up with a fairly close fitting opaque hood, with an internal reflecting surface. The type of reflector illustrated serves very well for this purpose. If the distribution of light from this lamp be determined and plotted in a Rousseau diagram it is found to agree very closely with the Rousseau diagram for the arc lamp.

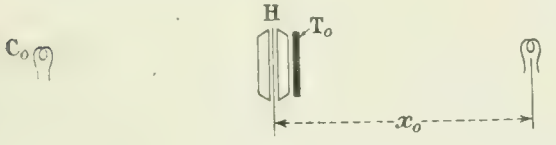


FIG. 3.

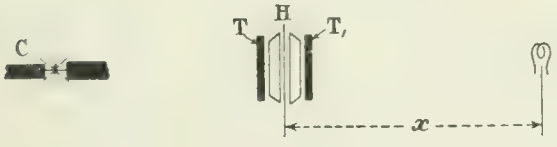


FIG. 3*a*.

When calibrating the cube, the arc lamp and all other accessories are left in place and the standard lamp is supported with its axis horizontal in place of the carbons. The positive carbon-holder serves to clasp the socket of the standard lamp in such a position that the light is emitted as desired towards the inside back wall of the cube. The method of determining the average candle-power of the hooded standard lamp is in accordance with the usual photometric procedure. The particular lamp illustrated gives an average candle-power of 422 candles at 240 volts with its hood in position.

The burning of the arc lamp inside the cube gradually causes a discoloration of the white walls, and it is therefore necessary to determine the constant of the cube each day by calibration with the standard lamp. The fixing of the large standard lamp for calibration purposes is rather cumbersome, and it has been found convenient to use an ordinary tungsten lamp without hood for the daily calibration, correcting the result by the previously determined ratio between the results given by the two lamps. It so happened that in the N.P.L. cube the two standard lamps gave identical constants. It must not be assumed, however, that this will always be the case, though from the conditions prevailing it is to be expected that the two constants will approximate to the same value.

The comparison lamp L is an ordinary grid filament vacuum lamp operating at 200 volts.

During calibration it is at a distance of approximately 2,000 mm. from the window E. The iris diaphragm G has an opening of 70 mm. and it must be remembered that the neutral filter T and the colour filter T_1 are removed during calibration. It is desired to express the constant of the cube in terms of a factor which (when there is a photometric balance) can be divided by the square of the distance x, in order to give the average candle-power in absolute units of the source of light in the cube.

(Fig. 3) Let C_0 = average candle-power of the standard lamp;
t_0 = transmission coefficient of neutral filter T_0 on the comparison lamp side;
x_0 = distance on scale to give balance.

Then in balance we have: $C_0/K = t_0/x_0^2$,

or
$$K = \frac{C_0 x_0^2}{t_0} \quad \ldots\ldots\ldots \text{(i)}$$

(Fig. 3*a*) Let C = average candle-power of arc;
t = transmission coefficient of neutral filter T on cube side;
t_1 = transmission coefficient of colour filter T_1 on comparison lamp side.

Then in balance: $Ct/K = t_1/x^2$,

or
$$C = \frac{K t_1}{x^2 t} \quad \ldots\ldots\ldots \text{(ii)}$$

Hence, since t and t_1 are known and K is found from equation (i), this equation gives C in terms of x.

During the calibration of the cube, the arc lamp cables, and any other objects ordinarily in the cube remain in position.

7. *Measurement of crater brightness.*—In Fig. 4,

A is the crater;
N is the positive lens (1·5 diopters) of radius r, at a distance a from the crater, and of transmission coefficient n;
O is a mirror of reflection coefficient m;
P is a xylonite screen with negative system of lenses at Q;
H′ is a photometer and T′ the colour filter of transmission coefficient t';
L′ is a comparison lamp of candle-power C′ at a distance x' from the photometer;

Let B be the normal brightness of the crater in candles per sq. mm. Then the lumens incident on the positive lens from the crater

$$= B \text{ (area of crater) } \pi r^2/a^2$$

Therefore lumens transmitted $= B \text{ (area) } \pi r^2 n/a^2$.

Hence the illumination at the image on the screen at P

$$= \frac{B \text{ (area of crater) } \pi r^2 n m}{a^2 \text{ (area of image)}}$$

but $$\frac{\text{(area of crater)}}{\text{(area of image)}} = \frac{a^2}{x_1^2}$$

Therefore the illumination at $P = \frac{B \pi r^2 n m}{x_1^2}$ mm. candles,

and the illumination at $H' = \frac{B \pi r^2 n m}{x_1^2 R}$ mm. candles,

where R = illumination at P ÷ illumination at H', determined

(*a*) by actual measurement using a portable brightness photometer;

(*b*) by measurement of magnification and allowance for the absorption of light in the lens system Q;

(*c*) by substituting for the arc a 500-watt "Pointolite" lamp, the surface brightness of a part of the plate of this lamp having been previously determined in candles per sq. mm. on a standard photometer bench by measurement of the candle-power of the known small area of its surface viewed through a pinhole of accurately determined diameter.

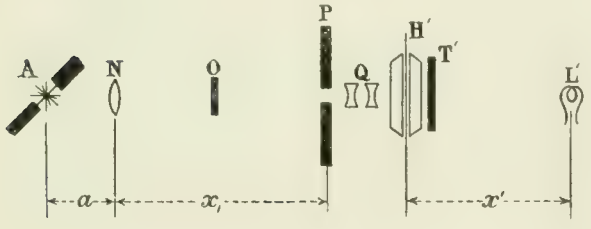


FIG. 4.

Also, illumination at $H' = C' t'/(x')^2$,

therefore $$\frac{B \pi r^2 n m}{(x_1)^2 R} = \frac{C' t'}{(x'_1)^2}$$

or $$B = \frac{C' t' (x')^2 R}{\pi r^2 n m} \cdot \frac{1}{(x')^2}$$

8. *Errors in measurement of total flux.*—The probable overall error of the final value of average candle-power is made up of the errors introduced at the different stages of the measurements as follows:—

(*a*) Determination of the average candle-power of the standard lamp used for calibrating the cube. No colour difference is involved in this determination and the value of the candle-power in terms of the unit accepted in England, France and America will be correct to ± 0·75 per cent.

(*b*) Determination of transmission coefficient of the neutral filter T. This causes a reduction of the light to approximately 2½ per cent. There is no colour difference and the result may be taken as correct to ± 1 per cent.

(*c*) Determination of transmission coefficient of the colour filter T_1. There is a considerable colour difference here, and the mean of the determinations of several observers must be taken. The error of the final mean may be regarded as correct to within ± 2 per cent.

(*d*) Photometric determination of the constant of the cube. The value obtained is merely the average of a number of ordinary photometric settings and the error may be taken as ± 0·5 per cent

The probable error in the final value assessed for the constant of the cube may therefore be put at 3·5 per cent, and this covers the probable error of the instruments used as distinct from the errors of observation. To this must be added, for any one carbon, the probable error of the series of observations upon it. This varies according to the individual peculiarities of that type of carbon and no general figure can be given for all carbons. Some types run more steadily than others, and in some the variations between individual specimens are considerable.

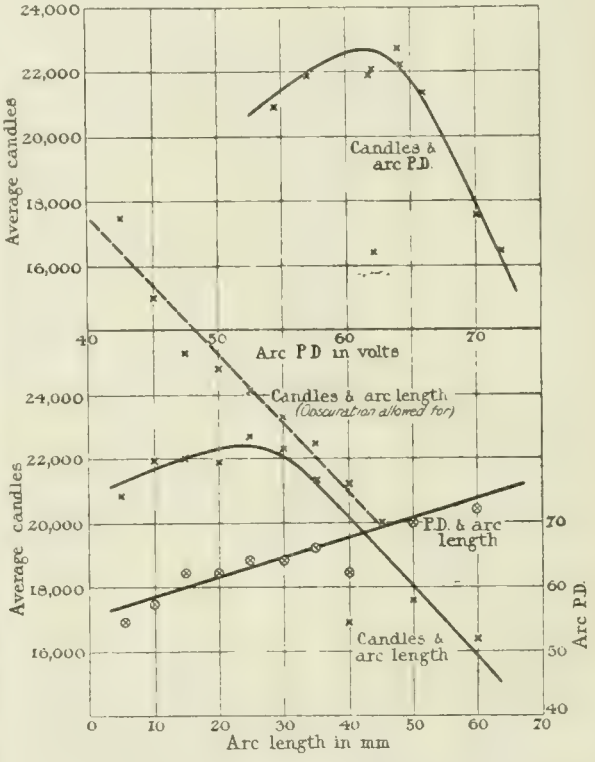


FIG. 5.—Variation of candle-power with potential difference and arc length (for Carbon IX).

G.E.C. "Apostle" carbons (+ ve 28 mm. —ve 26 mm.) impregnated, at 180 amperes.

II. RESULTS.

9. *General.*—In Table 1 is given a list of the carbons which have formed the subject of this investigation. The first seven were originally supplied for a comparison of their light efficiencies with that of a special impreg-

TABLE I.

No.	Description	Diameter mm. Positive	Diameter mm. Negative	Area sq. mm. Positive	Current Rated	Current Amperes per sq. mm. 0·2	Current Amperes per sq. mm. 0·3	Average Candles Rated Density	Average Candles Amperes per sq. mm. 0·2	Average Candles Amperes per sq. mm. 0·3	Candles per ampere Rated Density	Candles per ampere Amperes per sq. mm. 0·2	Candles per ampere Amperes per sq. mm. 0·25	Candles per ampere Amperes per sq. mm. 0·3	Crater Brightness Candles per sq. mm. Rated Density	Crater Brightness Candles per sq. mm. Amperes per sq. mm. 0·2	Crater Brightness Candles per sq. mm. Amperes per sq. mm. 0·3	*Minimum Arc Length	Candles per Watt Amperes per sq. mm. 0·25	Candles per Watt Amperes per sq. mm. 0·3
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
	Uncoppered Positives																			
I	Cored	20	9	314	90	63	91	10,400	6,300	11,000	115	100	111	117	180	160	184	14	1·8	1·9
II	Solid	22	12	380	60	76	114	5,250	7,600	13,300	87	100	110	116	145	152	170	20	1·7	1·8
III	Impregnated and Cored	23	12	415	110	83	125	12,600	8,550	14,800	114	102	112	118	161	152	161	20	1·9	2·0
IV	Cored	24	16	455	75	91	136	7,600	9,700	15,900	102	106	112	116	155	161	178	27	1·6	1·6
V	Cored	28	14	615	110	123	—	12,100	14,100	—	110	111	122		154	162	—	21	1·9	—
VI	Cored	32	16	805	150	161	—	17,100	18,800	—	114	117	125	—	155	160	—	24	1·7	—
VII	Solid	38	20	1,135	150	227	—	15,500	26,000	—	103	114	—	—	157	163	—	30	—	—
	Coppered Positive																			
VIII	Solid	28	16	615	—	123	185	—	11,800	24,000	—	96	117	130	—	139	183	35	1·7	1·7
IX	Impregnated, solid .	28	16	615	—	123	185	—	13,000	23,300	—	106	118	126	—	142	174	26	1·9	2·0
X	Solid	28	16	615	—	123	185	—	14,500	25,500	—	118	131	138	—	150	179	40	1·8	1·9
XI	Impregnated, solid ..	28	16	615	—	123	185	—	11,400	20,000	—	92	105	113	—	138	169	26	1·6	1·7
XII	Cored	28	16	615	—	123	185	—	9,800	22,000	—	80	107	123	—	130	179	26	1·6	1·9
XIII	Cored	28	16	615	—	123	185	—	9,100	22,100	—	74	118	121	—	174	187	28	1·6	1·9

* This length is the minimum at which the arc will burn steadily or which will give 7 per cent obscuration, whichever is the greater.

nated carbon developed by Messrs. W. Heape and H. B. Grylls, and described by them in Patents Nos. 126,673 and 128,057 of 1919. Subsequently, and as the result of conclusions drawn from these tests, a series of carbons was specially made up and supplied by the General Electric Co., Ltd., with the object

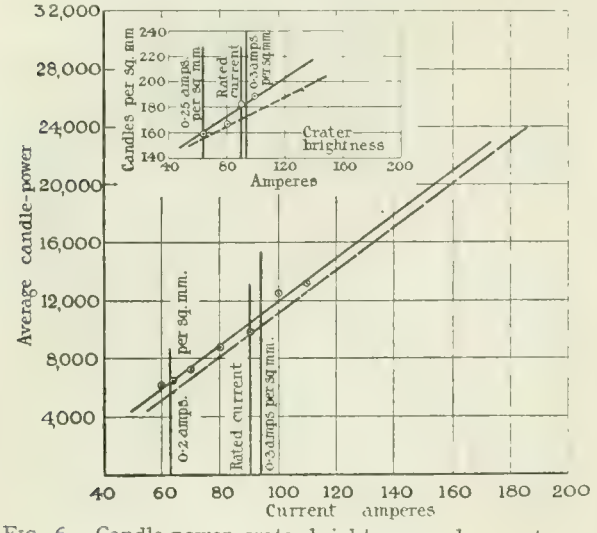


FIG. 6.—Candle-power, crater-brightness, and current curves (Carbon I).

Type of carbon	+	−	*Rated current*	*Inclination*
Plain	20 mm. cored	9 mm. solid	90 amps.	Carbons axial

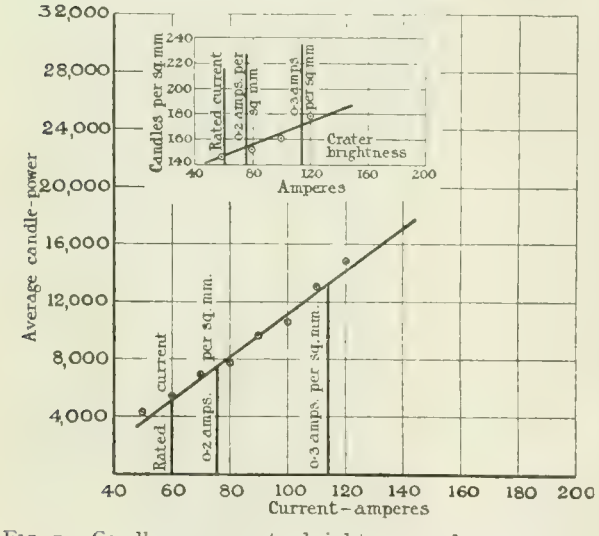


FIG. 7.—Candle-power, crater-brightness, and current curves (Carbon II).

Type of carbon	+	−	*Rated current*	*Inclination*
Plain	22 mm. solid	12 mm. cored	60 amps.	Carbons axial

of obtaining the best type of carbon for an average burning current of 200 amperes.

Tests were also made with the electromagnetic control device developed by Captain Yorke of the London Electrical Engineers.

The lamp in which the carbons were burned was an old Crompton type for the 90 cm. searchlight with automatic and hand-feed gear. During the test all feeding was done by hand by means of a chain and sprocket wheel driven from outside the cube.

It is seen from the table referred to that the rated current densities for the different carbons vary greatly, and while it was of course desirable to obtain

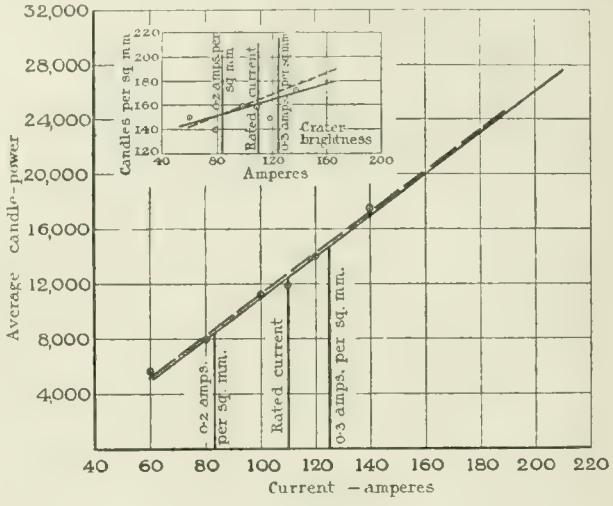


FIG. 8.—Candle-power, crater-brightness, and current curves (Carbon III).

Type of carbon	+	−	*Rated current*	*Inclination*
Impregnated	23 mm. cored	12 mm. cored	110 amps.	Carbons axial

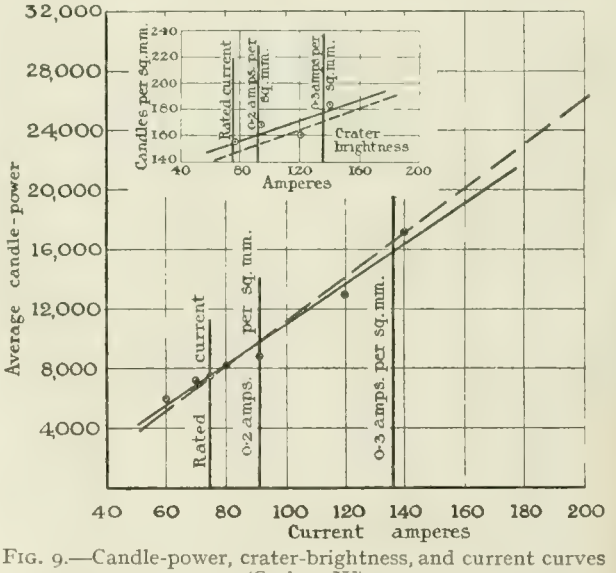


FIG. 9.—Candle-power, crater-brightness, and current curves (Carbon IV).

Type of carbon	+	−	*Rated current*	*Inclination*
Plain	24 mm. cored	16 mm. cored	75 amps.	Carbons axial

data on them at the normal rating, it was obviously necessary to test them at different currents and arc potentials.

10. *Variations of candle-power with potential and arc length.*—It was at first thought that the candle-power would vary both with the potential across the arc and with the current, but a careful investigation showed

that, while the potential difference and the arc length increased or diminished together, a large change in these quantities within the range of normal working produced no sensible alteration in the average candle-power.

Fig. 5 shows a series of measurements of the average candle-power from 28 mm. impregnated "Apostle"

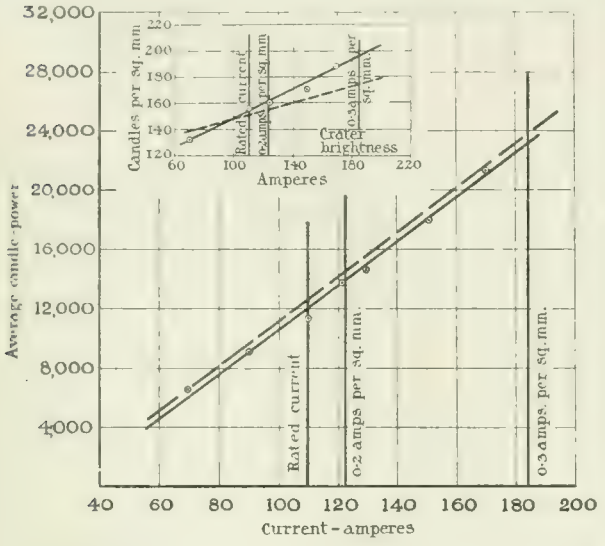


FIG. 10.—Candle-power, crater-brightness, and current curves (Carbon V).

Type of carbon	+	−	*Rated current*	*Inclination*
Plain	28 mm. cored	14 mm. cored	110 amps.	Carbons axial

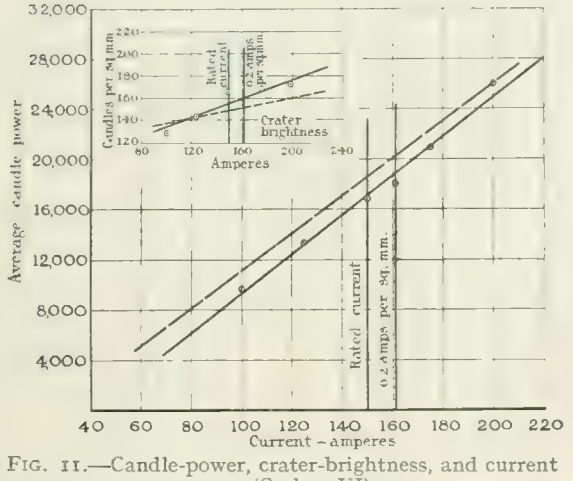


FIG. 11.—Candle-power, crater-brightness, and current curves (Carbon VI).

Type of carbon	+	−	*Rated current*	*Inclination*
Plain	32 mm. cored	16 mm. cored	150 amps.	Carbons axial

carbons when taking 180 amperes at arc potentials varying from 55 to 72 volts. The points corresponding to arc lengths less than 35 mm. cannot be said to indicate a definite variation of candle-power in either direction. The exact form of this curve may not be repeated in all cases, but it is clear from the observations shown, and others made subsequently, that an increase in arc length or potential difference does not produce any increase in average candle-power. It is true that for different arc lengths there are different degrees of

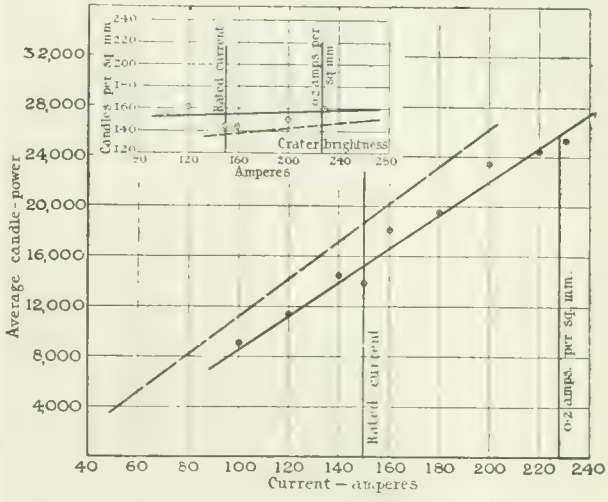


FIG. 12.—Candle-power, crater-brightness, and current curves (Carbon VII).

Type of carbon	−	−	*Rated current*	*Inclination*
Plain	38 mm. solid	20 mm. cored	120–150 amps.	Carbons axial

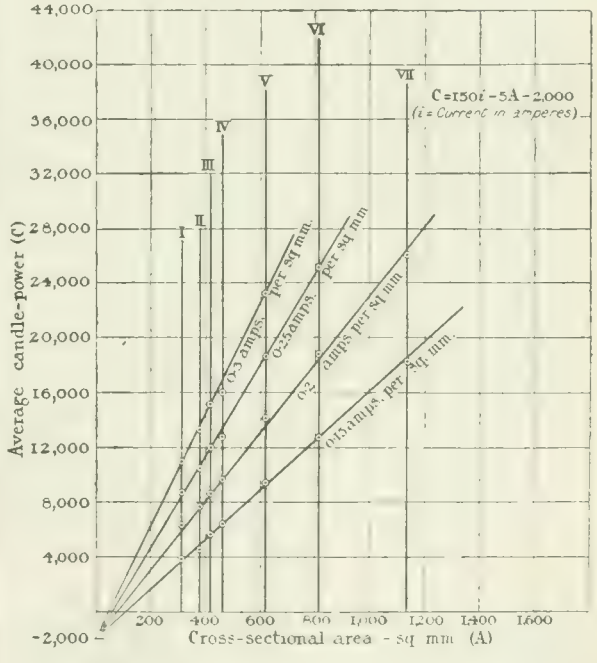


FIG. 13.—Average candles and nominal area of uncoppered positive carbons at four current densities.

obscuration of the positive by the negative carbon; it is of interest, however, to note that if the obscuration be allowed for and a curve of average candle-power be continued as indicated in the dotted line, the candle-power increases as the arc length is reduced. Mrs. Ayrton * also found that with large currents the candle-

* "The Electric Arc," p. 327.

power increased as the arc length was diminished. Hence the maximum candle-power *in any given direction not obstructed by the negative* is greater the shorter the arc length.

The fact that candle-power is virtually independent of the arc potential results in a simplification of the problem since one important variable is thereby eliminated. The arc length can therefore be adjusted to whatever point gives smoothest running, with the proviso that it should not be short enough to cause excessive obscuration, say more than 7 per cent. Although the average candle-power in all directions is not sensibly affected by change of arc length owing to the balance between obscuration and increase of candle-power, the fact that all the obscuration takes place within the solid angle embraced by the projector mirror renders it still important to avoid too short an arc.

The usual practice throughout these investigations was to open out the carbons until the arc ceased to hiss, the resulting arc length usually being greater than the minimum necessary to avoid more than the 7 per cent obscuration as indicated above. Certain impregnated carbons, however, run satisfactorily at exceedingly short arc lengths, and for these the arcs were adjusted to avoid excessive obscuration.

11. *Crater brightness and current.*—The points on the individual curve sheets showing the relationship between crater brightness and current have been connected by a straight line in order to indicate the general rise of brilliancy with increase of current, but the results are not sufficiently accurate to justify any assumption as to the true form of this relationship. It is clear that if, as seems very probable, the (candle-power)/(current) relationship is linear, and if that of the (crater area)/(current) is also linear, as has been shown by Mrs. Ayrton for small arc lengths and currents, then the (brightness)/(current) relationship must be of the form $(Ai+B)\div(Ci+D)$, and it is actually found that a function of this form suits the observations as well as the straight line indicated on the curves. In fact, using the values of the constants available, the differences between the values given by the two lines are well within the limits of experimental error.

It should be noted that the slope of the reference

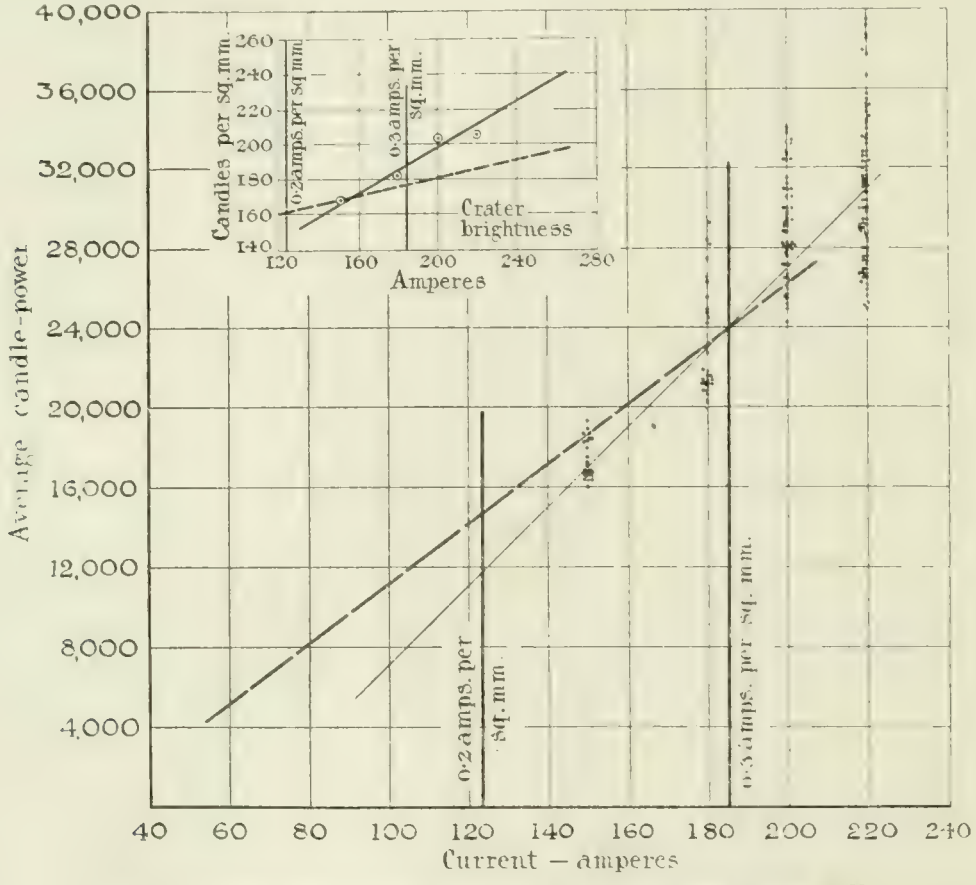


FIG. 14.—Candle-power, crater-brightness, and current curves (Carbon VIII).

Type of carbon	–	–	*Rated current*	*Inclination*
Plain	28 [illegible] solid cored	16 [illegible] cored	—	Cylindrical axial

line in the crater brightness curves depends on the size of the carbon with which it is compared, and diminishes as its diameter increases. This follows from the explanation given in par. 13.

The general position may therefore be summarized as follows :—

A long arc, for any given carbon, whether from impregnated carbons or not, implies a high potential ; and a short arc, a low potential. In order to obtain, under working conditions, a given amount of light from a given positive carbon, it is only necessary to pass through it a given current, the voltage across the arc and the arc length required to avoid hissing being immaterial. A positive carbon taking 200 amperes at 70 volts, i.e. 14 kw., will emit the same light as one taking 200 amperes at 100 volts, i.e. 20 kw. From the point of view of light emission from the positive crater, the extra 6 kw. are wasted. In order to ensure, however, that all but a very small proportion of the light directed towards the mirror from the positive carbon misses the negative, it is necessary for the arc length to exceed a certain minimum figure (for a particular diameter of positive and negative carbons), as mentioned in par. 10 above, and to obtain carbons which will take the maximum current through the positive crater at this minimum arc length, thus securing all the light possible with the minimum amount of dissipation of heat at the arc.

12. *Differences in light emission.*—The above discussion leaves out of consideration any specific differences there may be in the light emission of different carbons, i.e. in the capacity of one type of carbon to give more light than another for a given current.

The whole investigation shows that, for the types of carbon considered, there is no sensible difference either in average candle-power or in crater brightness for carbons of the same diameter run at the same current. The efficiency in candles per ampere, however, increases somewhat for the same current density as the diameter of the positive carbon is increased ; it is reasonable to attribute this, at least in part, to the greater relative cooling surface of the smaller carbons.

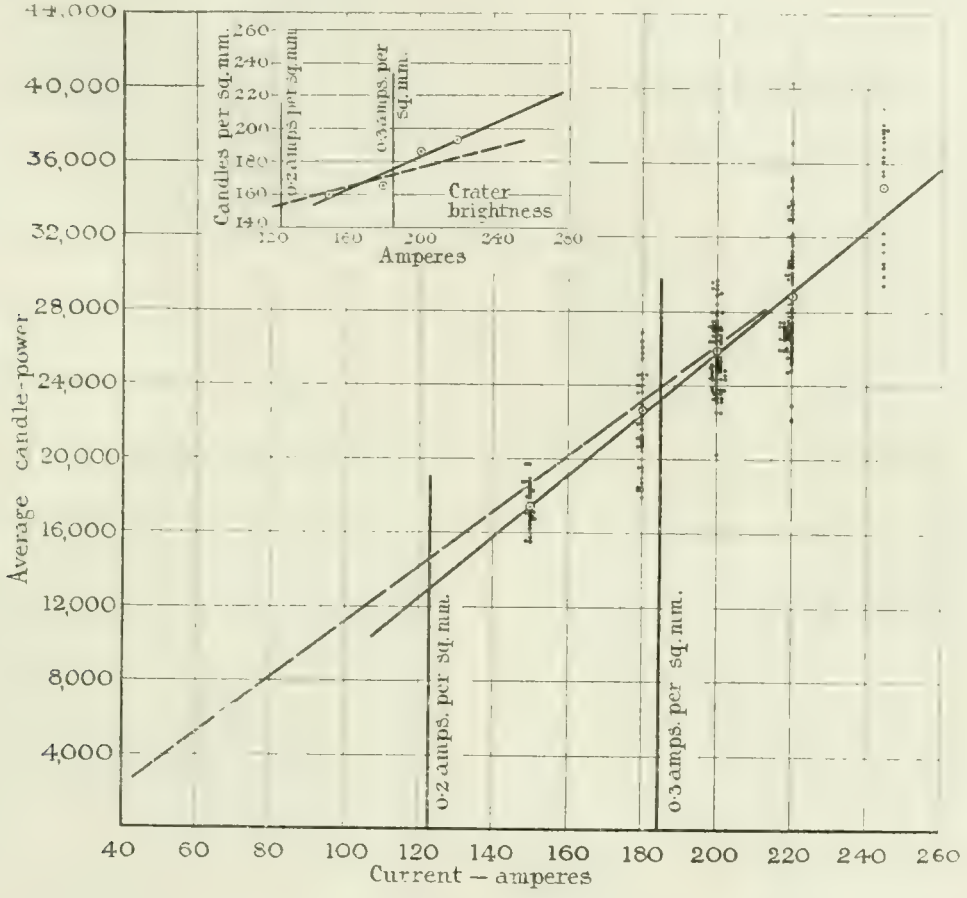


FIG. 15.—Candle-power, crater-brightness, and current curves (Carbon IX).

Type of carbon	+	−	*Rated current*	*Inclination*
Impregnated	28 mm. solid coppered	19 mm. cored	—	Carbons axial

13. *Curve sheets.*—The above conclusions follow from an examination of the curves in Figs. 6 to 19. The large curves are for average candles plotted against current; the small curves at the top of the sheet are for crater brightness in candles per sq. mm. plotted against current. Each curve sheet gives for one of the types of carbon the result of a long series of measurements of candle-power and crater brightness at different values of current. The (candle-power)/(current) curve for carbon No. II, when burned with the Yorke electromagnetic control, has been taken as a convenient reference line for purposes of comparison between other carbons, and this has been shown as a broken line on all curve sheets. For crater brightness a dotted reference line has been drawn by connecting two points whose co-ordinates are obtained thus: the abscissæ are the currents corresponding to densities of 0·2 and 0·3 ampere per sq. mm. of the carbon considered, while the ordinates are the crater brightnesses of the reference carbon at the same current densities. It will be seen that the figures of crater brightness agree satisfactorily with those obtained by Forrest.*

Each circle marked on the curves represents the mean of a large number of observations. Usually a series of 10 observations was made at a given current, over a 10-minute period of burning. The current

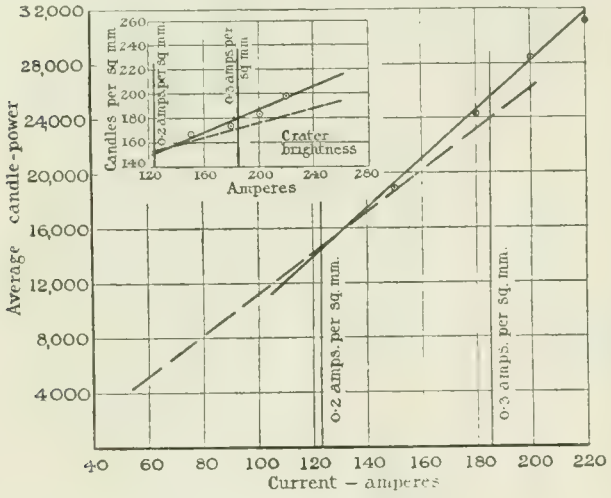


FIG. 16.—Candle-power, crater-brightness, and current curves (Carbon X).

Type of carbon	+	–	*Rated current*	*Inclination*
Plain	28 mm. solid coppered	16 mm. cored	—	Carbons axial

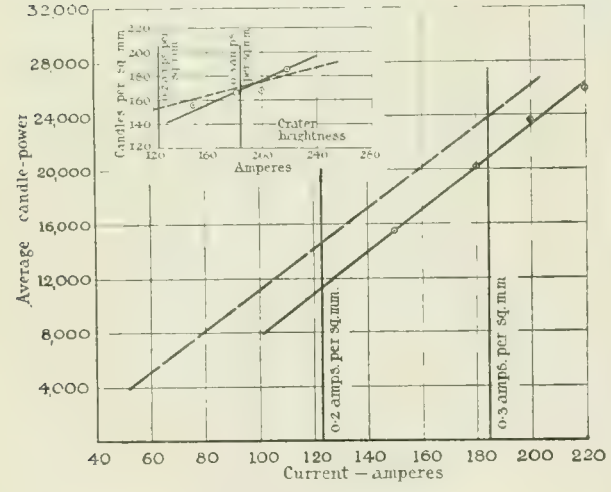


FIG. 17.—Candle-power, crater-brightness, and current curves (Carbon XI).

Type of carbon	+	–	*Rated current*	*Inclination*
Impregnated	28 mm. solid coppered	16 mm. cored	—	Carbons axial

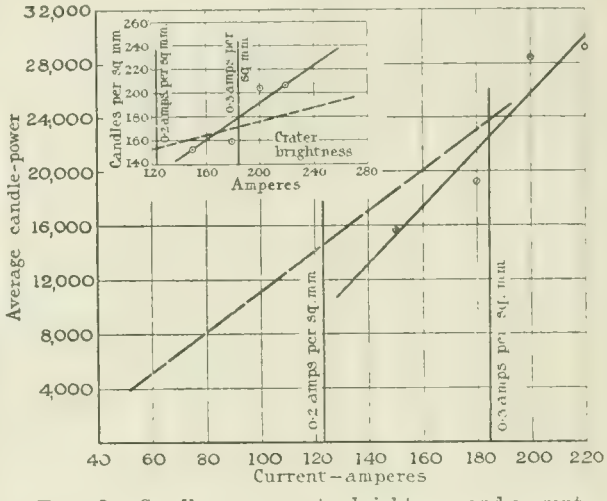


FIG. 18.—Candle-power, crater-brightness, and current curves (Carbon XII).

Type of carbon	+	–	*Rated current*	*Inclination*
Plain	28 mm. cored coppered	16 mm. cored	—	Carbons axial

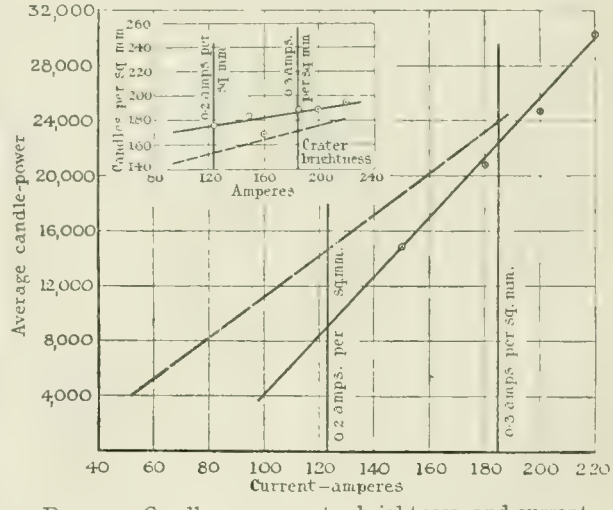


FIG. 19.—Candle-power, crater-brightness, and current curves (Carbon XIII).

Type of carbon	+	–	*Rated current*	*Inclination*
Plain	28 mm. cored coppered	16 mm. cored	—	Carbons axial

* *Electrician*, 1913, vol. 71, pp. 729 and 1007.

value was then changed and a further series taken after the conditions had settled down at the new current. The first current was then repeated either on the same carbons or on a duplicate set. Usually the results plotted on any curve represent some 5 or 6 pairs of carbons burned in this way.

14. *Individual variations.*—It has not been thought worth while as a rule to show individual observations on the curve sheets, but for the purpose of illustration this has been done for the (candle-power)/(current) curves in Figs. 14 and 15 for the solid coppered carbons. Attention was concentrated on currents of 150, 180, 200, and 220 amperes and, in the case of one of them, of 250 amperes. At each of these currents it is seen that the emission of light from these carbons was liable to vary over a wide range. For instance, at 200 amperes, omitting isolated readings, there is an extreme variation of some 30 per cent for normal burning conditions.

Smaller carbons appeared generally to vary much less than the larger ones, but in either case no reliable comparison is possible unless the mean of a large number of readings is taken.

III. Comments on the Behaviour of Individual Carbons.

15. *Uncoppered carbons (Nos. I to VII).*—

(I) Fig. 6.—This was a French cored carbon made by the Sautter, Harlé Company, 20 mm. in diameter, rated at 90 amperes—a relatively high density of 0·29 ampere per sq. mm. This carbon gave uniformly smooth and flexible running without the use of the electromagnetic device at arc lengths varying from 5 to 30 mm. and at currents varying from 60 to 110 amperes. The potential difference across the arc ranged from 54 to 72 volts varying with its length and also, to a small extent, with the current. The efficiency of this carbon (candles per watt consumed in the arc) at a current density of 0·3 ampere per sq. mm. was higher than that of any other unimpregnated carbon, being 1·9 candles per watt at an arc length (14 mm.) giving not more than 7 per cent obscuration.

(II) Fig. 7.—This was a solid Army carbon (G.E.C. "Apostle" grade) 22 mm. in diameter rated at 60 amperes per sq. mm. On the whole, good running was obtained; without the electromagnetic device currents up to 100 amperes could be taken, and with this device it was possible to run up to 130 amperes. The potential difference across the arc ranged from 50 to 80 volts for arc lengths varying from 10 mm. to 40 mm. and with currents varying from 50 to 120 amperes. The results on this carbon have been used as a reference as stated in par. 13.

(III) Fig. 8.—This was a cored carbon (G.E.C. "Nubia" grade) of 23 mm. diameter, impregnated with the Heape and Grylls special solution. It was rated at 110 amperes or a current density of 0·265 ampere per sq. mm. It was found to give good flexible burning with the electromagnetic device for arc lengths ranging from 3 to 20 mm. and currents varying from 60 to 140 amperes, the potential difference across the arc being 50 to 62 volts.

The efficiency of this carbon at an arc length of 20 mm. (7 per cent obscuration) was 2·0 candles per watt at a current density of 0·3 ampere per sq. mm.

(IV) Fig. 9.—This was by the same maker as No. I, but possibly of a different composition. It was 24 mm. in diameter, and its rating was 75 amperes, or 0·165 ampere per sq. mm. This also gave good burning without the electromagnetic device, but was not so uniform as the smaller carbon. The arc length ranged from 8 to 23 mm., and the currents from 60 to 140 amperes, the arc potential difference ranging from 50 to 72 volts.

(V) Fig. 10.—This was a Navy cored carbon ("Apostle" grade) of 28 mm. diameter, its rating being 110 amperes, or 0·18 ampere per sq. mm. This carbon ran very smoothly without the electromagnetic device for arc lengths of 14 to 32 mm. and currents varying from 70 to 170 amperes, the potential difference ranging from 55 to 76 volts.

(VI) Fig. 11.—This was similar to the foregoing but of 32 mm. diameter. Its rating was 150 amperes, or 0·186 ampere per sq. mm. This carbon did not give very good running as the arc was difficult to control. The arc length and potential differences ranged from 10 to 35 mm. and from 60 to 86 volts respectively, while the current varied from 100 to 300 amperes.

VII. Fig. 12.—This was an Army solid carbon ("Apostle" grade) 38 mm. in diameter, its rating being 150 amperes, or only 0·132 ampere per sq. mm. This arc was often difficult to control and gave irregular results at currents above 200 amperes. The arc length varied from 15 to 30 mm. for currents of 120 to 230 amperes, and the arc potential difference from 60 to 86 volts. It was impossible to get currents exceeding 230 amperes to run steadily.

16. *General remarks on carbons I to VII.*—Fig. 13 gives a set of curves embodying the results of the average candle-power tests on the seven uncoppered carbons referred to above. It is seen that for all these carbons the average candle-power depends only on the current and the nominal area of the positives. The empirical expression obtained for these curves is of the form $c = A\,i + B\,a + C$, which gives the average candle-power for any carbon in terms of the current and area, where i is the current and a is the nominal cross-sectional area of the positive in sq. mm. For these carbons A = 150, B = −5, and C = −2,000.

Hence it is seen that the average number of candles per ampere tends to increase with the area for a given current density. Thus,

$$\text{candles per ampere} = 150 - \frac{5}{i/a} - \frac{2{,}000}{i}$$

and if i/a (i.e. current density) is constant $= p$, then

$$\text{candles per ampere} = 150 - \frac{5}{p} - \frac{2{,}000}{p\,a}$$

It appears that no appreciably greater efficiency can be obtained by increasing the diameter of the positive beyond 28 mm., since the rate of increase at this point in candles per ampere for a large percentage change in the diameter is very small.

Further, as a result of this investigation it was found

that the maximum current which any uncoppered carbon could carry without overheating was given approximately, for the sizes used, by the empirical formula

$$i_{max} = 1{\cdot}8\, d^{1{\cdot}4}$$

where d was the diameter of the positive in mm. By comparing this with the expression for candles per ampere given above, it was found that the maximum candles per ampere should be obtained with a positive 34 mm. in diameter taking some 250 amperes. This gave 124 candles per ampere, a result almost identical with that obtained with the 28 mm. diameter carbon at 154 amperes, viz. 123 candles per ampere. This is also evident from Table 1 (see cols. 14 and 15).

The fact that the candle-power values for each current density lay regularly on a system of straight lines showed that none of these carbons possessed any noticeable superiority in specific light emission. It may be noted that coppered negatives of smaller diameter could be used with some advantage with Nos. IV and VII, say 12 and 18 mm. respectively, since this would reduce the obscuration of light which would otherwise reach the projector mirror.

All the positives were uncoppered, and it was found that as the current density was increased beyond about 0·3 ampere per sq. mm. the carbons became very hot, especially the larger sizes, and began to disintegrate on the outer surface. For further work at high current densities and to use carbons of 28 mm. diameter, therefore, it was decided to have all the positives coppered.

17. *Coppered carbons (Nos. VIII to XIII).*

(VIII) Fig. 14.—This was a carbon of 28 mm. diameter, of the same grade as No. II but with a copper coating approximately 0·06 mm. thick. The coating enabled this carbon to be run satisfactorily at a higher current density (up to 0·36 ampere per sq. mm.) than solid uncoppered carbons of the same grade. The current ranged from 150 to 220 amperes while the arc length varied from 20 to 65 mm., and the potential across the arc from 64 to 98 volts. The efficiency of the carbon at an arc length of 35 to 40 mm. (the minimum for a current density of 0·3 ampere per sq. mm.) was 1·7 candles per watt.

(IX) Fig. 15.—This was a carbon of 28 mm. diameter similar to No. VIII but impregnated with the special Heape and Grylls solution and without any coring.

As in the case of No. III, this carbon gave very good and flexible running with the electromagnetic device which was necessary to keep the arc from wandering. The current ranged from 150 to 250 amperes, the arc lengths from 6 to 60 mm., and the potential difference across the arc from 56 to 78 volts. Hence it followed that this carbon could be run with a very short arc and correspondingly reduced potential difference, though this involved an increased obscuration by the negative carbon (see par. 19). This carbon was also run without the electromagnetic device, but with the positive rotating at a uniform speed of about one revolution per 2 minutes while the negative was inclined at an angle of some 25° with the horizontal. The effect of removing the electromagnetic device and adding the rotating device was slight, as the latter kept the crater regular, the only difference being that the position of the arc with regard to the crater could not be controlled, though with a short arc this control appeared to be unnecessary.

The efficiency of this carbon was 2·0 candles per watt at a current density of 0·3 ampere per sq. mm. and an arc length of 26 mm. (7 per cent obscuration).

(X) Fig. 16.—This was a solid carbon of 28 mm. diameter and of a harder grade than No. VIII (G.E.C. "Nubia"). It was run with the electromagnetic device with a range of current of from 150 to 220 amperes, with a potential difference of from 68 to 98 volts and arc lengths of 30 to 70 mm. The results were similar to those obtained with the No. V carbons, except that a higher current density and consequently a higher candle-power were obtained. A long and consequently unstable arc was required for currents of 200 amperes and over—in fact some 5 mm. longer than in the case of the No. VIII carbon. It was also found that this grade of carbon tended to chip while burning.

(XI) Fig. 17.—This was a solid coppered carbon, 28 mm. in diameter and was the same as No. X except that it was impregnated with the special solution. It was run at currents varying from 150 to 220 amperes with a potential difference of from 58 to 68 volts and arc lengths of 14 to 22 mm. There was no difficulty in burning this carbon at any arc length and the potential difference only varied slightly with the length and current. The average candle-power, however, was distinctly lower than that of No. IX.

(XII) Fig. 18.—This was the same as No. V except that it was coppered. It was run at currents from 150 to 220 amperes and a potential difference ranging from 58 to 86 volts with an arc length of 25 to 42 mm.

(XIII) Fig. 19.—This was a cored carbon of 28 mm. diameter and was also run at currents ranging from 150 to 220 amperes and a potential difference varying from 48 to 74 volts with arc lengths of 10 to 40 mm. The running was fairly good, though the candle-power was lower than that of No. VIII for the same current.

18. *General remarks on carbons VIII to XIII.*—The thickness of coppering on the carbons VIII to XIII was 0·06 mm. This apparently resulted in an increase in the slope of the (candle-power)/(current) curves, and in shifting the intercepts on the axis of the current. This last was equivalent to an increase in the size of the carbon. It is probable that the relative irregularity of the results was due to the difficulty in maintaining a uniform crater at current densities exceeding 0·3 ampere per sq. mm. Carbon IX had the greatest efficiency in candles per watt, and Nos. IX and XI had the greatest flexibility of burning. At 220 amperes the average candle-power of these six carbons did not differ by more than 13 per cent from the mean. In all cases the negatives were of 16 mm. diameter and heavily coppered, as it was found that if smaller ones were used the coppering volatilized and the carbon gradually disintegrated and diminished in diameter when the current exceeded 180 amperes.

19. *Obscuration of light by the negative carbon.*—It is clear that at some of the shorter arc lengths employed during the course of the investigation, the proportion of light obscured by the tip of the negative carbon

cannot be altogether neglected. The amount of this obscuration can be readily calculated if it be assumed that (i) the positive crater radiates as a circular disc emitting light according to the cosine law (i.e. the radiation in any direction is proportional to the cosine of the angle between that direction and the normal to the radiating surface), and (ii) the negative may be regarded as a circular disc parallel with the positive and at a distance from it equal to the arc length. Of these assumptions the first is probably very close to the truth for all ordinary carbons, as, if internal reflection be neglected, the radiation from a hollow surface is the same as that from a plane of the same apparent area, i.e. a cup-shaped crater gives the same radiation in any direction as a flat crater of the same diameter and of equal surface brightness. The second assumption is open to question on two counts: (*a*) the diameter of the negative carbon becomes considerably reduced at the end, and (*b*) the effect of obscuration by the stem of the negative carbon with its holder is neglected.

Another effect, which tends to offset the result of the reduction in diameter of the negative, is the reduction in the diameter of the positive carbon. These effects, which to a certain extent will counteract one another, will only modify a value that is, in itself, a correction, so that they have not been considered as of sufficient importance to justify the labour of calculation in more than a single case.

Neglecting these corrections, the percentage of the light emitted from a positive crater of diameter D which is obscured by a negative of diameter d at an arc length a is given by the formula:—

$$\frac{50}{D^2}\left\{(D^2+d^2+4a^2)-\sqrt{(D^2+d^2+4a^2)^2-4d^2D^2}\right\}$$

The values of this expression for three different sizes of negative, and at all arc lengths, are given in the curves of Fig. 20, where all dimensions are expressed in terms of the diameter of the positive. Thus, for a 28 mm. positive the obscuration values of a 16·8 mm. negative are given by the curve marked $d=0{\cdot}6$, and thus 7 per cent obscuration is exceeded in the case of all arc lengths shorter than $1{\cdot}0\times28$ mm. $=28$ mm. There is one other consideration which cannot be neglected. For a 36-inch projector of about 16·5 inches focal length, only 70 per cent of the total light from the crater falls on the mirror. All the obscured part of the light is within the angle embraced by the mirror so that the effective obscuration of the useful light is 1·4 times that given by the formula, i.e. in the example cited above the obscuration is approximately 10 per cent.

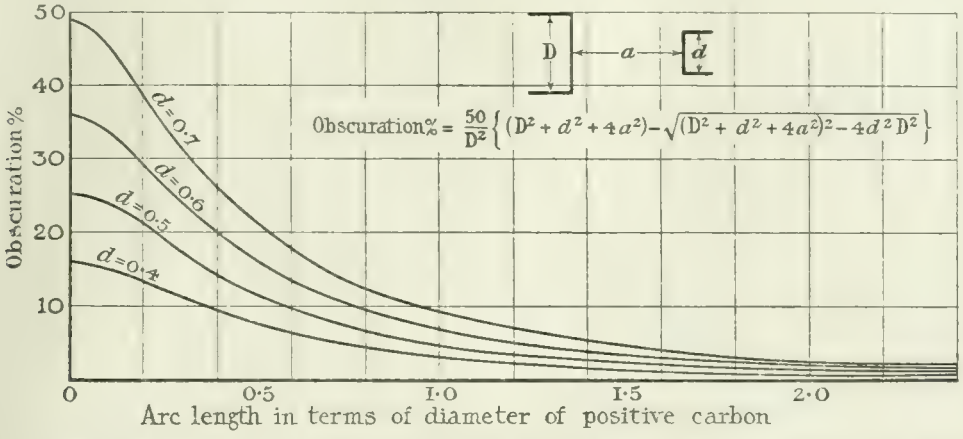


FIG. 20.—Curves showing percentage of the total light emitted from a radiating circular disc of unit diameter, which is obscured by a co-axial circular disc of diameter d situated at a distance a from, and parallel to, the radiating disc.

[NOTE.—All dimensions are in terms of the diameter of positive carbon.

The thanks of the authors are due to the Admiralty for permission to make public the results contained in this paper.

DISCUSSION.

Captain J. K. im Thurn, R.N.: We all know how research work in connection with searchlights is complicated by many variables, the most important of which, namely, the effect of atmospheric conditions, is not only infinitely variable in itself but is not under the control of the investigator. Again, the application of results is often compromised owing to limitations which have to be imposed on the final design of a projector and its fittings. A naval projector and fittings must be absolutely reliable, simple in construction, easy to handle, and capable of withstanding extremely severe concussion. Naval projectors have frequently to be mounted within a few feet of the muzzles of our largest guns. I have known cases where the blast from these guns has wrenched fittings off the barrel of the projector. Unfortunately, atmospheric conditions at Teddington render it impracticable to carry out searchlight tests under actual working conditions, namely, with the lamp in a service projector and the projector out of doors. Such tests must always be the

final criterion in a problem of this nature; it was therefore arranged for H.M.S. "Vernon" to carry out practical outdoor tests at Portsmouth. These tests have now been in progress for several months and much valuable experience has already been gained. The work carried out at the National Physical Laboratory, as described in the paper, has been of the greatest assistance to the "Vernon" in carrying out the practical tests. The N.P.L. results point to the fact that any carbon, no matter what its actual composition, will give the same total light as any other type of carbon when burnt under exactly similar conditions. "Vernon's" outdoor tests confirm this. Again from the N.P.L. results one would expect in practice to get a considerable increase in the intensity of the beam for a given current by reducing the size of the crater. "Vernon" trials to date show that this increase is not so marked as one might have expected. This points to the fact that the majority of the extra total light given by carbons under these conditions does not reach the mirror and is therefore mostly wasted. The National Physical Laboratory has made very careful measurements of intrinsic brilliancy of the crater. From the figures the relative intensity of the beams produced from various carbons can be ascertained, but unfortunately the diameter of the crater is not stated in any instance; consequently the relative divergence of the beam cannot be estimated, and a knowledge of this is essential before an opinion of the relative value of a carbon for searchlight work can be formed. Experience shows that the crater of a 20 mm. carbon is reduced in a smaller proportion than that of a 28 mm. carbon. Hence the diameter of an unburnt carbon gives us no definite clue as to the size of its crater when burning. Our ultimate aim is to determine the type of arc which will pick up and hold a target at the greatest range, and this involves a careful study of the effect of atmosphere. The Army and the U.S. military authorities are co-operating with us in this work. Our results to date appear to show that the yellower light emitted from arcs burnt at 0·3 ampere per sq.mm. and less, is subjected to slightly less absorption than the bluer light from higher current-density arcs. The proposed improved methods of measuring absorption will, we hope, definitely settle this point. To sum up, our general conclusions to date point to the high-current-density arc (0·7 ampere per sq. mm. and above) as being the most suitable for long-range work, particularly if the carbon manufacturers can produce carbons which will give rays rich in the wave-lengths least affected by absorption. The National Physical Laboratory has been asked to investigate flame arcs, and we look forward to receiving their results.

Mrs. Ayrton: I am particularly interested in this paper because I have had much experience in investigations on searchlights and arc lighting for cinemas. When, in 1903, Professor Ayrton was first asked by the Admiralty to draw up a specification for searchlight carbons which would make the country independent of foreign supplies, there was very little knowledge of large-current arcs to draw upon, and the carbons made in England were all so bad that he had to spend a year in making chemical analyses, comparing specific gravities, etc., and instructing the General Electric Company on the subject, before they could make carbons even equal to the foreign types. Times have changed since then. Of the three types of carbons sent to him for comparison only one had been made in England; while the authors of the present paper had seven types, of which only one was foreign. In seeking Professor Ayrton's co-operation, the Admiralty thought it possible to prescribe every single condition under which the arcs were to be constrained to burn, down to the coppering of both carbons to a thickness of nearly 0·2 mm. The present experimenters are asked to "determine what improvement can be made either in the carbons themselves or in the methods of burning them." It was long before Professor Ayrton could even get the Admiralty to realize the importance of having the tips of the carbons made by the manufacturers to the shapes that they normally acquire and retain, when burnt with the required current and potential difference. Perhaps the full importance of this normal shaping is scarcely yet realized, and that may account for the extraordinary variations of candle-power in Figs. 14 and 15. The authors' surprise at finding the candle-power practically constant over a certain range of length of arc, with a constant current, is somewhat unexpected, because as long ago as 1893 Professor Ayrton announced this fact* at Chicago, in connection with much smaller currents, it is true. Again, in 1897 Monsieur Blondel,† after an elaborate and beautiful series of experiments which should be studied by everyone interested in arcs, published curves showing similar results; and other experimenters have since done the same. One of the most important deductions made by the authors is the following:—"The whole investigation shows that, for the types of carbons considered, there is no sensible difference either in average candle-power or in crater brightness for carbons of the same diameter run at the same current" (page 93). This statement conflicts so seriously with the figures, that it is difficult to see how it ever came to be made. The comparison is only possible with the arcs run with coppered positives, since of the uncoppered ones no two were of the same diameter. But even with the former the figures show wide differences both in candle-powers and in crater brightnesses. Take the current of 123 amperes. The average candle-power varies (Table 1) from 9,800 to 14,500—some 48 per cent—and the crater brightness from 130 candles to 174 candles—26 per cent. With the current of 185 amperes the percentages are somewhat less, but still considerable. The average candles vary from 20,900 to 25,500—22 per cent—and the crater brightness from 169 to 187 candles—11 per cent. With neither current, therefore, does the deduction appear to be warranted, nor is it borne out by my own experience. Passing to the efficiencies of the various arcs, which the authors have measured by the ratio of the candles to the power consumed in the arc, I should like to call their attention to the fact that this ratio, while a very interesting one from a scientific point of view, is no measure of the true efficiency of the arc. In very early days it was recognized that a resistance was required in series with

* "The Electric Arc" p. 329.
† *L'Eclairage Electrique*, vol. 10, pp. 289, 496, 539.

the arc, if it was to burn steadily; and I have shown * that such a resistance is not merely needed to "steady" it, as was supposed, but that without a certain minimum resistance in series with it no silent arc can be maintained at all, and that this necessary resistance is greater the longer the arc, and the smaller the current, and varies with the type of the carbons. The power consumed in this inevitable resistance is, then, an integral part of the power required to maintain the arc; and it is the ratio of the candles to the sum of the powers consumed in the arc itself and in this outside resistance that is the true measure of the efficiency of the arc. As this outside resistance has ordinarily to be more than enough to include that of the leads, switches, etc., the efficiency may generally be taken to be simply the ratio of the candles to the power expended by the generator. To take an example: I have found that with currents up to 150 amperes with lengths of arc suitable for searchlights, the potential difference at the terminals of the generator has to be from 20 to 25 volts higher than the potential difference across the arc. If even only the lower value was needed for the most efficient arcs employed in the present investigation we find that the true efficiency of the 125-ampere arc with carbons III (Table I), and of the 185-ampere arc with carbons IX was 1·5 instead of 2·0. Thus *the most efficient of the arcs examined was 25 per cent less efficient than a half-watt lamp.* This result comes as a great surprise to me, as it will, I think, to many others. It is quite possible that the extremely careful light tests applied by the experimenters have shown that the arc is a far less efficient source of light than is usually supposed; but also, possibly, the arcs were not burnt under the best conditions for the particular carbons under trial. The first hypothesis can only be tested by further experiment; but the paper itself gives data by means of which the second can be determined. Carbons I to V were so evidently unfit to carry any current approaching 200 or even 185 amperes, that one wonders why those particular sizes were chosen. What is to be learnt, for instance, from carbons rated at 90 amperes when one is looking for those that will run well with 200 amperes? Nothing but that, run at their own rating and under their own conditions, they maintain a good steady arc. If, indeed, after having found this, other carbons of the same type, but of diameters sufficient to carry 200 amperes, had been made, and tested under their own best conditions, then an immense amount of knowledge would have been gained. It is usual, in scientific investigations, to change only one variable at a time. This is not possible in the case of the arc; if one alters the diameter of the positive carbon, in order to use a larger current with safety, the diameter or constitution, or both, of the negative must also be altered, and in all probability the potential difference across the arc will require to be changed too. These changes are inevitable; but why make an extra one that was not inevitable? Why copper the positive carbon, when all those smaller ones had been uncoppered? How is it possible to tell whether any given effect was produced by enlarging the positive or by coppering it? Had coppered and uncoppered positives of the same size, with their appropriate negatives, been tried, of each type, each pair under its own best conditions, what a store of information we should have gained from investigators who take such immense pains over their experiments. But not even the best conditions were applied in every case. With one of the uncoppered positives that the authors found unsatisfactory, I have made many most satisfactory experiments with currents up to 150 amperes; but it was with a different negative, and at least some of the other conditions were different although I used the same type of lamp and projector as the authors. As my experiments were eminently satisfactory, enabling me to maintain a perfectly steady arc on the automatic feed (a much more severe test than hand feeding) during the whole 4½ hour lives of the carbons, I think I may claim that my regime was the right one. I made no absolute tests of the light with these carbons; but I made comparative tests against the light given out by another of the pairs of carbons tested by the authors, and found with a current of 120 amperes that my carbons gave something like 50 per cent more light, at the expense of about 20 per cent more power. I believe that, under the proper conditions, these carbons would afford a more efficient arc than any of the pairs with coppered positives tried in this investigation. It seems to me that investigators have gone off on quite a wrong tack in turning to coppered positives; even these experiments show that the efficiency of the arc is not increased thereby; but it would take too much space to give my other reasons here. Much that I should like to say about negatives, which are so important, but which receive such scant attention now, I must also omit. One word I must say. There are usually, at the present time, at least three variables in a negative—a core, an outer shell and a copper coating. In order that such a negative may, with any given current, remain intact, except where it is actually burnt by the arc, its resistance must be so low that the temperature produced by the mere passage of the current is less than that required to oxidize the copper coating. Why, then, with three variables and all the possible combinations of them at their disposal, do present-day investigators almost invariably turn their whole attention to the copper coating, when they want to increase the current sent through a given carbon? That is much easier than finding by experiment how the other variables might be altered, but the result is disastrous when it leads to such heavy coppering that the mirror is injured by falling drops and the arc by too much copper vapour. Experiments which require the making of large varieties of experimental carbons, with their sizes and the proportions of their variables differing, are tedious and lengthy; but in the long run I think they pay better than simply piling more and more copper on to carbons made for smaller currents.

Captain J. Paley-Yorke: The paper is really a comparison of carbons without reference to the searchlight beams which are produced by them, and I suggest that a more suitable title for the paper would have been "Carbon electrodes for use in searchlights." The results are, however, very interesting and valuable, namely, that with different carbons, there is very little difference in the total flux of light and in the

* "The Electric Arc," p. 250.

intrinsic brilliance of the crater. It should be very comforting to those of us who were actively associated with the searchlight in warfare to feel that there is at least one factor in connection with the searchlight which can be regarded to some extent as constant. Unfortunately, however, the total flux is certainly not a criterion of the ability of an arc to give a high-intensity beam in a searchlight, though I agree that the intrinsic brilliancy might be more of a measure, if we were sure that the craters were of equal shape, equally luminous per square millimetre of surface, and that we had no disturbing factors such as flame or fume, and difference in quality. The authors recognize some of this, I think, for on page 85, col. 1, par. 4 of the paper they say "the more important factor is . . . the average candle-power of the crater in directions embraced by the mirror." I submit that even there the authors do not go far enough. Surely it should be the proportion of the average candle-power in the angle embraced by the mirror which will fall upon the mirror in such a direction that it would be reflected back again within the angle of dispersion required in the beam. Unfortunately that is often a very different thing indeed. My opinion is that there is only one way of comparing arcs for searchlight purposes, and that is by burning the arc in the searchlight in the manner in which the authors had originally intended, and which they abandoned when they came across some of the difficulties. I do not wish to minimize those difficulties; indeed, I could add to the schedule which the authors set forth, but it was quite impossible for us not to face them, and we have taken thousands of readings on outdoor work. In par. 3 (*a*) to (*f*) the authors have given a schedule of the difficulties of outdoor work. I admit that 3 (*a*) is a very great difficulty indeed, but we had to meet it by always having one arc as a standard of reference, by having skilled personnel and careful rehearsals of our scheme of operations; first taking the standard beam, then the beam which was being tested, then back again very rapidly to the standard beam, and back again to the beam being tested. Night after night we repeated this performance and compared the results. We found that if on one night beam A was twice as good as beam B, on another night beam A would again be twice as good as beam B, although the readings were taken under entirely different conditions. We came to our conclusions after we had taken dozens and dozens of tests with carbons A and carbons B. Then again we might find with beam A and beam C that the relationship was not always the same, that sometimes C was half as good and sometimes it was three-quarters as good, and so forth. Even that was of the greatest value, for it showed us the danger, or perhaps the advantage, of using some particular form of impregnation in the carbon. I refer in particular to Table 1 on page 89 and carbons VIII and IX. It will be noticed that carbons VIII and IX, indeed all the carbons, differ very little from one another; but we found in our tests that those two particular carbons differed tremendously from one another—so tremendously that we could have no hesitation in rejecting that one which was always the worse. I have not time to go into the other objections which the authors have raised, but every one of them can be, and was, overcome. May I say, in conclusion, that one rather gathers the impression from the paper that such improvements as the reduction in the diameter of the carbons, the coppering of the carbons, and the abolition of the core, were introduced by the National Physical Laboratory. I am quite sure that such an impression was not meant to be conveyed, but I think I may be pardoned if I state that these improvements were introduced by the Anti-Aircraft Searchlight Experimental Establishment of the War Office, attached to the London Electrical Engineers, at a date prior to the tests of which this paper is a report.

Mr. H. B. Grylls: The most interesting point in the paper is, I think, in Fig. 5, which deals with a great many variables. In the curve of candles and arc lengths it is pointed out that practically no difference in candle-power exists when arc lengths are considered of from 10 mm. to about 35 mm. in length. That is true; but there is a very considerable difference in the crater areas produced at those various arc lengths, and as the potential differences across the arc are also very different, we can get a guide as to the most economical carbon from the point of view of power consumption in watts. Further, as Mrs. Ayrton has just said, there is certainly no question that with a short arc we have a more intense crater. I may add that on one occasion when Mr. Heape and I were working on beams at Brooklands, we found that one of the most intense beams was obtained with a cored carbon while the tip of the negative carbon was actually inside the crater—a very deep crater, of course. We used a rotating positive electrode, but whether the positive was rotated or not we always found that the shorter the arc the easier it was to manipulate. I do not know whether with Captain Yorke's device that would hold good. It also had the advantages of having a smaller potential difference across it, and we invariably found that we got a more intense beam. That, of course, only refers to the conditions when one is attempting to get a beam of the smallest diameter, that is to say the smallest divergence possible. In Fig. 5, if we compare the potential differences across arc lengths of 10 mm. to 30 mm., we see they are 58 and 65 volts respectively, and these figures refer to a carbon impregnated by the process for which Mr. Heape and I are responsible. I have always found that carbons impregnated have a lower potential difference at any particular arc length than carbons not impregnated, and they are still lower with cored positives. Captain Yorke made a great point of measuring beams as against the carrying out of laboratory measurements. We tried measuring the intensity of beams for some considerable time at very short range—a range of some 50 yards—and we gave it up as quite hopeless owing to the fact that an arc is not a point-source of light, and hence that the distribution of light in the beam does not settle down within 300 yards or so of the searchlight. The only beam tests that can be of any use are long ones, something like 500 yards for preference. It is almost always impossible to get 500 yards without the objections raised by the National Physical Laboratory, and there-

fore we look forward very much indeed to the time when the laboratory carries out what is foreshadowed in the early part of the paper, namely, to increase the scope of their tests by measuring the illumination falling upon different concentric zones of the mirror. When that is done a proper calculation can be made, which ought to give the intensity and distribution of the beam obtained from that carbon.

Mr. Haydn T. Harrison: I wish to congratulate the authors on their extremely ingenious design for carrying out measurements of carbons, but I cannot add the words "for searchlights." The actual requirements of a searchlight are not spherical candle-power, but only 20 per cent. of the sphere. Although it is stated that the second object of carrying out these tests was to develop a method of testing in order to prove their value for searchlights, the method of testing adopted, unfortunately, cannot prove their value for searchlights, because it does not give any indication of the one quantity we want to know, namely, the luminous flux which will fall on the mirror of the searchlight. This had been borne out by some of the most important investigators. For example, Jean Rey, who has done much work in this particular branch, definitely stated that there could be no factor which would reduce spherical candle-power or total luminous flux to the actual value of the flux reaching the mirror. Therefore it is impossible for anybody to ascertain, from the results of these tests, the relative value of these carbons for searchlight work. The alternative method put forward is the intrinsic brilliancy of the crater. Captain Yorke has already stated that that would have been of some assistance in turning this work into practical value if we had known the actual diameters and configurations of the craters, but as these are not given it is impossible to apply the cosine law; and even if one could, again referring to Jean Rey and others, the brilliancy of the crater is not uniform. The figures of brilliancy given here, which corroborate many other published figures, are, I conclude, average intrinsic brilliancy. I should like the authors to tell us exactly how they define the edge of that particular area over which the brilliance was taken. The authors' reasons for abandoning the open-air tests I can thoroughly appreciate, but they make a statement which seems to me rather extraordinary, namely: "The various sources of uncertainty in the conditions were sufficient to mask such differences completely." If we turn to the results we shall find that the differences in candle-power per watt, for instance, are as much as 10 per cent. It is said that the instrument which it was necessary to use if the searchlight's open beams were to be considered, could only be considered correct within 5 per cent, plus or minus. Therefore, in the actual results they were testing, there was a divergence of 10 per cent., and the instruments they were using for that beam test would also be liable to vary by 10 per cent. It naturally follows that they would not perceive the difference in the beam when measured in that way. But, as Captain Yorke has pointed out, the difference is very much greater in the actual beams than appears from the results given in the paper. I am particularly sorry that this method of testing was adopted, because of the fact that one cannot utilize the values as I had wished to utilize them for measuring the luminous flux on the mirror; but I do not wish in any way to depreciate the value of these tests or the paper, as it will always have value as proving certain points which had been considered by some people to be open to question. I am also rather sorry that the figures have been stated in candle-power; by luminous flux is not generally meant candle-power, and anybody reading Table 1 would be very much misled, because it does not say whether spherical or hemispherical candle-power, or maximum candle-power is referred to, therefore when they see a result such as two candles per watt they would put down the efficiency of the lamp as about equal to that of a gas-filled incandescent lamp as made to-day, which is far from correct when searchlights are mentioned or considered.

Mr. M. Solomon: I take a very different view from that expressed by Mr. Harrison or Captain Yorke. I quite agree that the ultimate test of carbons for searchlights or of searchlight arcs is only to be obtained by actual measurements on the beam under working conditions: but having had a very long experience of the work which has been done in this country on searchlight testing, I have no hesitation in saying that no finality would ever be reached if experimenters were to confine themselves to this method. The problem is excessively complex, and it can only be tackled by dealing with the various parts of it separately, and there are a large number of those parts which can be, and in this instance have been, dealt with very satisfactorily under laboratory conditions. The authors set out to explore one particular aspect of searchlight arcs, the question whether, in what is known as an ordinary carbon arc, the composition and to some extent the treatment of the carbon made any very material difference. I think the paper has cleared up to a very large extent that question by showing that the composition does not make any material difference. I regret that the authors have not given more data. I should like to know very much in connection with all these carbons the diameter and the shape of the crater. I appreciate that that is a difficult thing to define, but even an approximate measurement would have been very valuable. I am quite sure, however, that in the case of carbons Nos. VIII and X, where the difference in composition is very radical, the differences in the craters would not have been sufficiently great to vitiate the result and that there is no appreciable difference in the value of those two carbons for searchlight work. This assumes of course that other things, such as steadiness of burning and so forth, are equal. I was very much surprised at this, because of the result which the National Physical Laboratory obtained many years ago when they investigated these two qualities of carbon at low current densities on behalf of my Company. They then found that carbons of the composition of No. X were 25 per cent better than carbons of the composition of No. VIII, and I must confess that it was a great surprise to me to find that at these very high current densities that result no longer holds. I should therefore like to emphasize that point again, that I believe this paper, by isolating that particular aspect of the problem, has cleared the ground and made future work much more

easy and much more likely to progress. I should like to touch on one other point. Fig. 5 shows that if obscuration can be avoided the shorter the arc the better is the light obtained. In some of these carbons one cannot burn a short arc because the arc begins to hiss. In other words, we are up against a definite physical property of the arc which prevents us going below a certain length. In other carbons such as the impregnated carbons, one can use as short an arc as one desires. The avoidance of obscuration is here not a physical question—Mrs. Ayrton has pointed out that it corrects itself to a large extent—it is a mechanical question ; and therefore it is not fair, in my opinion, to compare such impregnated carbons with unimpregnated carbons on the basis of an arc length which is determined by obscuration, because in the one case we are dealing with a physical factor, and in the other case it is nothing of the sort.

Professor J. T. MacGregor-Morris : I agree with Mr. Solomon in thinking that the way in which the authors have tackled the subject is the surest one, i.e. to divide the problem into its separate parts and settle these step by step. The final problem, as has been stated by a number of speakers, is to determine the efficiency of a carbon searchlight in the open in actual use, but that is a very much larger problem. I will touch on one or two points rapidly. First of all, I see that owing to mist in the air large variations have been found. I should like the authors to state at what height above the ground these measurements were made. As they were made in Bushey Park, apparently they have been made over grass, where moisture would be more prevalent than in the streets of a town. I am considering these variations with regard to the question of the photometry of lamps in streets. Is the question of the obscuration by the atmosphere an important one when the distance is only something like 100 or 200 feet ? Then I should like to ask, with regard to the tests on the carbons in the photometer, whether they were dried out before they were used. It is known that it is very essential to dry out carbons before use. Mr. Forrest found in my laboratory that if we wanted to get an arc to burn as quietly as possible it was important to heat the carbons to a red heat in an electric furnace, allow them to cool down, keeping them in a fairly air-tight chamber, and then to use them as required. I suppose that none of these arcs were what would be called silent arcs. Then with regard to the details of errors, have comparisons of calibrations of the cube been made with a tungsten vacuum lamp, secondly, with a tungsten nitrogen-filled lamp, and thirdly with a tungsten arc or " Pointolite " lamp ? What kind of variations in the constant would be obtained in the cube photometer for different polar distributions and different qualities of the light emitted. These would be useful figures for other investigators engaged on cube photometers. Then I think it would be an advantage to give more details with regard to the positions of the shutters in these cube photometers. It is absolutely essential in photometers, especially where one is doing high-pressure gas testing, to have good ventilation. Next, with regard to the discolouration of the cube photometer, was that due to heat, and if so, how much did the constant vary throughout the tests ? On page 87, expressions are given for the transmission coefficient of neutral and coloured filters. Will the authors state in their reply the values of these coefficients and what variations they found in them ? I have personally found in arc-lamp photometry that it is better to do away entirely with coloured screens and measure the direct beam, and also to do away with mirrors if one possibly can. From a comparison of the results of various observers I find that the degree of precision obtained is quite as high as that which is obtained when coloured screens are used, and the results are more reliable. The figures for the intrinsic brightness of the crater are most interesting, particularly in view of the work which many observers have done in connection with the electric arc, and the following table collects the results of various investigators arranged in chronological order.

Investigator	Candle-power per sq. mm.	Remarks
Abney	39–116	
Trotter	80–170	
Blondel, 1893 ..	160	
Petavel, 1899 ..	147	0·06 to 0·26 ampere per sq. mm.
Forrest, 1913 ..	162	Silent arcs, about 8 amperes solid carbon
,, 1913–14 ..	172–174	Silent arcs, about 8 amperes solid carbon
Paterson and others, 1919	156* / 178†	Slightly humming arc, 100 to 200 amperes, solid carbon

* 0·2 ampere per sq. mm. † 0·3 ampere per sq. mm.

The authors' figures range between 156 and 178 c.p., so that it appears that the values obtained with currents of about 8 amperes and with currents of 100 to 200 amperes are substantially the same.

Mr. A. P. Trotter : Trial in open country must be the ultimate test of a projector. The meadows of Teddington are hardly the right place : I should like the work to be carried out from Leith Hill to Box Hill, and so get rid of the mists. This research is of great interest, but seems to relate to carbons generally rather than to carbons for searchlights. It is very interesting, as showing there is very little difference between the carbons, and it is probable that the intrinsic brilliance will also follow, and that is what is wanted. I cannot understand why the authors give so much attention to the total flux when dealing with projectors. Barring such things as smoke and irregularities, intrinsic brilliance is the main thing to be considered. Theoretically, if we have a crater of one square millimetre and a good mirror, if viewed from a considerable distance it will appear full of light. It cannot be more than full. If the area of the crater is increased, all that we do is to increase the angle of the beam. It is a paradox, but the candle-power of the beam has nothing to do with the candle-power of the crater. Intrinsic brilliancy is the main thing. The authors have made some very

interesting experiments with the cube, but by using eight equilateral triangles of 840 mm. side cutting off each corner, one would get a much closer approximation to a sphere, because we know that the cube does not behave exactly as the sphere. No information is given in Table 1 about the area of the crater. The diameter of the crater is by no means the diameter of the carbon. Carbon wastes away at the end. In a research on the intrinsic brightness of the arc in 1894 I did not have any lens or mirror, but merely took a diaphragm with a small hole, and I put that in front of the crater at a sufficient distance away so as not to get it burned up, but at the same time as close as possible, and I simply received the beam through that. The candle-power per square millimetre of crater was very easily calculated. I very soon found that it was by no means uniform, especially when the arc was humming. If there was any humming at all there was a rotating bright patch in the arc, rotating from 100 to 140 times a second; part of that is a bright spot, and very different from the rest of the crater. For a silent arc 160 c.p. per sq. mm. is a very fair result. I am not surprised to find that the brightness is not constant for all current densities and sizes of crater, but I am not convinced that the straight line in Fig. 7 nor the other lines in the other figures give the true relation of intrinsic brightness to current density. Mr. Forrest in his work eliminated some of the difficulties by using very small carbons. The result of the authors' work would greatly help the study of electric arcs, which are falling out of use except for searchlights.

Major K. Edgcumbe: I feel that fully to appreciate this paper one must realize how very meagre were the data which the designer of a searchlight had at his disposal a few years ago. Therefore, although I fully agree with what Captain Yorke and Mr. Harrison say as to the mean spherical candle-power or the average candle-power not being the final criterion, at the same time to know that the average candle-power given out in all directions by any pair of carbons will be the same irrespective of their nature is an enormous advance. At the time when these experiments were being carried on I was at the War Office, and we were continually having suggestions made to us for an improvement of the carbons. It was very difficult either to prove or disprove the claims without very laborious tests. I should like to congratulate the authors on their self-restraint in having written a paper of 15 pages on the subject of an illuminant, without once mentioning the word "lumen" nor, as a corollary, introducing the term 4π. We seem to get on very well without either. The authors, very rightly I think, lay great stress on the question of crater brilliancy. That is really the crux of the whole problem. All modern developments in high-intensity arcs have been in the direction of forcing the current into the centre of the positive crater so as to increase the crater brilliancy. I hardly think, in this connection, that the authors have laid sufficient stress on that exceedingly simple and flexible method of doing this—namely the Yorke control, which is in my opinion the only practicable method of applying these high-intensity arcs to searchlights for anti-aircraft work. The authors several times speak of the carbons running "smoothly and flexibly," and so on, without control. This may be all very well under the watchful eye of the observers at Teddington, but I am inclined to think that these self-same carbons would prove much more stubborn under the conditions which existed on the Western Front, for example. The arc had to be available for use at any moment—the most important time being often the few seconds after opening out. One could not wait for the arc to steady down. Under these circumstances it is essential to have some special form of speed control, and the Yorke control enables one to do marvels. I am very glad to hear that Captain Yorke will explain it at a later date. Lastly, I should like to ask whether the authors have arrived at any definite decision as to the relative transmission of different coloured beams. When I was at school I was always told that the red beam penetrated best, and it was proved to me beyond doubt by showing that the sun when it was low in the sky looked red. I believe the more modern idea is that there are two different forms of absorption, that is to say, ordinary water vapour (or true fog) best transmits a white light, whereas solid particles, such as London smoke, best transmit a red light. Presumably the true criterion is the colour of a standard white surface when exposed to daylight which has passed though the atmosphere under investigation. If this is so, it should be possible, by means of some form of colour-matching arrangement, to collect valuable data under various atmospheric conditions. The subject is one of considerable importance quite apart from searchlight work, and merits more attention than it seems to have received.

Dr. H. F. Haworth: The arguments that have been put forward against outside testing are good, but results to have real value to searchlight designers should be obtained from the mirror. Could not some indoor method of testing using a mirror be devised? Too much emphasis has been given to total flux measurements; such curves are given greater prominence, and the more interesting curves from a searchlight point of view, the crater-intensity current curves, are relegated to a corner. Are these average values for crater intensity? If so, how does it vary over the crater? In testing for crater brilliance with current, would it not be better to choose a number of suitably graded carbons of the same composition, and measure the crater brilliancy when the crater occupies practically the whole end of the carbon? The comparison as it stands is hardly fair. With No. II carbon the crater brilliancy varies from 138 c.p. at 40 amperes to 175 c.p. at 125 amperes. Would the same thing have happened if the carbons had been so proportioned in each case that the crater had covered the whole carbon? I am inclined to think not, and would venture to predict that the slope of the crater-brilliancy curve would be very much reduced, if indeed it did not disappear altogether. Current densities are given in the paper as amperes per square millimetre of the carbon. Would it not be more informative if they were given as amperes per square millimetre of the crater? I should like to know if the authors have made measurements of crater area under the various conditions. It should be determined whether crater-area/current is a linear function

at high currents. May not the falling candle-power with increasing arc length be due to absorption of the light from the crater by the increasing volume of arc vapour? The statement on page 93 that a positive carbon taking 200 amperes at 70 volts will emit the same light as one taking 200 amperes at 100 volts seems to be rather contradicted by curve 5 which shows that 75 volts maintains a 50 mm. arc and 100 volts a 150 mm. arc. If the candle and arc length curve is continued downwards, it cuts the zero candle axis at 133 mm., so that the positive crater would be giving a negative illumination. No 2 carbon with Yorke control is used as the comparison standard for crater intensity. Are we to assume that all the curves were taken with the Yorke control on? If so, will the authors say what difference, if any, in crater brilliance is produced by this device. This appears to be one of the reference points of the work, yet nothing is said about the advantages, or otherwise, of this device over the standard control. If, as seems probable, the crater brilliancy is fairly constant over a wide range of current, then the size of the positive carbon is practically fixed for a given current, and we then have to produce a negative carbon which will burn at an equal rate. This is very important on account of the necessity of keeping the lamp in focus. The negative carbon is more difficult. For a 16 mm. carbon carrying 200 amperes, a reasonable case, the current density is 1 ampere per sq. mm., which is very severe. It is necessary to reduce the resistance so that carbon only has a reasonable amount of heat to radiate. In this case the copper sheath has to carry 90 per cent of the current. If the coppering is uneven, hot-spots develop, the copper oxidizes, and the carbon gets red hot and is soon destroyed. If there is too much copper, it is dangerous to the mirror. I hope the work will be carried on, as it is important that for the next war we should have thoroughly efficient searchlights.

Mr. A. E. Angold: Do the authors think it would be practicable to compare the brilliancy of the beams given by the various carbons by using a searchlight mirror focussed on a distant object until the beam is parallel and a white disc of the same diameter as the mirror placed in the centre of the beam at a short distance from the projector? I believe comparisons of the total candle-powers reflected by the disc would be more useful than measurements of the spherical candle-power and the brilliancy of the arc crater. Such tests would still be independent of atmospheric conditions. I agree that carbons should be first compared independently of atmospheric conditions and that the percentage absorption according to the colour of the light and under varying atmospheric conditions should be settled with a further series of tests. With regard to the 35 per cent variation of candle-power with the same carbons, do they think there is any means of getting the maximum as a normal thing; and in connection with the measured improvement of the brilliancy as the arc was shortened, is it safe to assume that the available candle-power would continue to increase if the obscuration by the negative could be kept constant? Is it not probable that the great depth of a short-arc crater increases the brilliancy, because the radiation is restricted to a narrow angle and because the long white-hot point which is formed on the negative reflects the heat back to the crater? Regarding long arcs, my impression is that there is some property of the negative arc stream which has a cooling effect when it strikes direct on the positive crater. A "Beck" arc crater has its greatest brilliancy when the negative stream is deflected entirely away from the crater and the electrical circuit is completed by the stream of gases evaporated and thrown out from the positive crater to meet the negative stream. This is also true if the special feature of the Beck arc—namely, the methylated-spirit flames surrounding the carbons—is absent. It would seem, therefore, that some of the carbons referred to in this paper might be capable of giving a more brilliant crater if the negative arc stream were deflected, but that would probably necessitate rotation of the positive carbon to ensure even burning. The arcs with the plain solid carbons would not burn steadily with a deflected arc, because the voltage drop in the arc stream near the positive crater is not sufficiently below the sparking voltage that would jump through the hot gases immediately surrounding the arc stream, but some of the other carbons could be worked with a deflected arc. The effect of deflecting the arc stream was forcibly brought to my notice. I was instructed to experiment with a 110-ampere Beck arc, but did not get a beam candle-power proportional to that obtained on the "Vernon" with a 150-ampere arc. This I found to be due to the smaller magnetic repulsion of the 110-ampere arc resulting in the negative arc stream impinging straight into the positive crater, but I also found any desired path for the arc stream could be maintained by varying the positions of the carbons and by passing the lamp current through conductors suitably placed with respect to the arc.

The Authors (*in reply, communicated*): We wish to express our sincere appreciation of the interesting remarks, and the exceedingly helpful proposals and suggestions which have been made in the course of the discussion, and of the kind way in which the paper has been received. We should like to thank those who have taken part in the discussion for the criticisms they have made: criticisms of a very helpful kind for the future work that is projected. We should also like to thank those who have defended the methods of experiment described in the paper.

The main criticism made by several speakers is the fact that the tests on these carbons have not been carried out in the open. We should be sorry if the impression were conveyed that we thought the methods described were the only methods which should be used in judging searchlight carbons. On the contrary, we have always recognized that open-air tests must remain the ultimate criterion of the efficiency of an arc for searchlight work, but we think there is little doubt that tests made in the way described in the paper give a much more speedy and reliable result than would be obtained from most of the tests which could be made in the open. We support the very strong plea which Mr. Solomon made, that tests in the open, unless very far more thorough and extensive than is possible in most cases, are exceedingly unreliable. We are familiar

with a great deal of Captain Paley-Yorke's work, and look forward with very great interest to hearing the result of it. He and his colleagues have put in an immense amount of labour, but we suggest that it is work such as Captain Yorke has done, combined with that which can be done in the laboratory, which enables one to form the only true judgment of the quality of different carbons.

Another point which has been raised by several speakers is the relative importance of total flux and of crater-brightness measurements. Some speakers, among them Mr. Harrison, have contended that it is total flux which really matters and this, no doubt, is true if a beam of given divergence is aimed at. It has, however, often been contended—though we believe that for military work, at least, this is no longer the case—that a beam of great concentration and high penetrating power is required, and for this, as Mr. Trotter remarks, the crater brightness is the only thing that matters. In this connection, it is interesting to notice that the valuable work Mr. Harrison has done on the vapour-cooled arc has all been directed towards the production of a crater of very high intrinsic brightness, and not primarily to the increase of the total flux emitted.

The question of the diameter of the positive crater has been raised by several speakers and its importance was not overlooked by the authors. There are, however, two points to be considered in this connection. Where the current density is very low, the edge of the crater is not at all well defined, and any measurement of crater brightness must of necessity be only approximate. For the higher current densities, however, the crater fills the whole of the positive carbon, and thus the crater area may be taken as that of the end of the positive in all cases where the current density is over 0·2 ampere per sq. mm. The only difficulty now is the decrease in diameter of the positive carbon at the burning end. The records of our measurements of crater diameter show that this does not exceed 5 to 6 mm. for a 28 mm. carbon burning at 0·3 ampere per sq. mm., and, further, that this decrease is sensibly the same for all coppered carbons of the same size burning at the same current density, so that for comparative purposes it results that the total flux and the crater brightness bear an approximately constant ratio to each other, and this agrees, generally, with the figures of Table 1 (coppered carbons).

The remaining points raised may best, perhaps, be discussed *seriatim*. Mrs. Ayrton referred to the time taken for carbons to shape themselves. It was always necessary to run the arc for at least 10 minutes, often longer, before a set of measurements was undertaken. The negative carbons used had a hard core in every case. They did not in every case burn away at exactly the same rate as the positives. The thickness of coppering of the positive carbons VIII to XIII is given in the paper as 0·06 mm.

With regard to the extra light emitted in the case of a very short arc, we do not agree that this can be attributed to the tapering of the negative as the arc length is diminished. If we refer to Mrs. Ayrton's book, the diagram* showing the shape of the negative at different arc lengths indicates clearly that for the 1 mm. and 2 mm. arcs the carbon diameters are, at equal distances from the crater, nowhere less in the former than in the latter, so that the amount of light obscured in the case of the 1 mm. arc must necessarily be greater than that obscured in the case of the 2 mm. arc, and though the relative amounts may, and probably will, not be exactly as given by the formula at the conclusion of our paper, yet it will be apparent from a glance at the diagrams referred to, that the light obscured by the negative of the left-hand diagram (1 mm. arc) is considerably greater than that obscured by the carbon of the central diagram (2 mm. arc). In fact, if the negative carbon of the latter figure be traced off and superimposed on the negative of the left-hand figure, it will be seen at once that, so far from the obscuration being less in the latter case, it must clearly be considerably greater.

We notice that Mrs. Ayrton in her revised reply has omitted any mention of this matter, but as her remarks at the meeting have been referred to in the technical Press we have thought it desirable to leave the above paragraph in our reply.

With reference to the statement made in the paper that the experiments showed "no sensible difference either in average candle-power or crater brightness for carbons of the same diameter run at the same current," we would point out that it has been stated that the coppered carbons were made up with the definite intention of investigating their suitability for use at 200 amperes and that at this current the extreme variation of average candle-power is only 20 per cent and of crater brightness less than 10 per cent. Considering the variation found between different individuals of the same type of carbon, it was thought that this variation was insufficient to indicate any definite superiority of one type over another.

With regard to the "efficiency" of the arc, we should like to point out that one of the chief difficulties in the use of a heavy current arc for searchlight work is the large amount of power actually consumed in the arc, and the consequent excessive heating of the mirror. Thus in the particular case of arcs for searchlight work, it is more desirable to know the power consumed in the arc itself than that actually required for the running of the arc. We agree, of course, that from the point of view of efficiency as measured in candles per watt consumed, the latter is the more important.

Carbons I to V were those originally in use in the British and French Services, and it was desired from experience gained with these to specify carbons for running at 200 amperes. Carbons VIII to XIII were the outcome of the results of the experiments on carbons I to VII. At first, carbons VIII to XIII were used uncoppered but, as in the case of the smaller carbons (p. 96, end of § 16) at 0·3 ampere per sq. mm. the carbons became red hot and it was therefore found necessary to have them coppered. The disadvantage of too thick a coating of copper was carefully borne in mind when this decision was made.

In reply to Captain Paley-Yorke, we may say that there was absolutely no intention of claiming priority in the introduction of any of the devices he mentions,

* "The Electric Arc," p. 324, Fig. 94.

at least one of which, as Mr. Grylls has stated, was suggested many years ago.

In reply to Mr. Harrison, the values of luminous flux emission given in the table are expressed in terms of average candle-power, i.e. mean spherical candle-power. The figure of 20 per cent given by Mr. Harrison as the proportion of the whole sphere covered by the mirror refers only to the solid angle. When account is taken of the polar distribution of the light from the arc, it is found that, as stated in the paper, the proportion of the total flux which reaches the mirror is of the order of 70 per cent for ordinary projectors.

In reply to Professor MacGregor-Morris, the axis of the beam used in the outdoor tests was approximately 6 feet above the ground, most of it over grass land. One would not imagine that for street-lamp photometry at distances of 100 to 200 feet the question of atmospheric absorption would be serious under any ordinarily clear condition. The carbons were dried out before use, but to a temperature of about 60° C. It was not considered advisable to take the temperature any higher than this in view of the fact that some of the carbons were impregnated. Any temperature approaching a red heat would, we imagine, be out of the question for such carbons. The question of the constant of the cube photometer is now being thoroughly investigated at the Laboratory and it is hoped very shortly to describe a method by which the constant of the cube for a given source can be predetermined from the polar curve of that source. It may be stated that for sources of the types mentioned by Professor Morris it has been found by this method that the theoretical cube constant does not vary by more than 5 per cent if the source is at the centre of the cube. The effect of the ventilating shutters will be investigated by the same method.

The transmission coefficients of the screens referred to in the paper were as follows :—

$t_0 = 10{\cdot}9_5\ \%$; $t = 2{\cdot}4\ \%$;
$t_1 = 16{\cdot}9\ \%$; $t' = 16{\cdot}1_5\ \%$; $m = 89\ \%$.

It will be noticed that only neutral screens were used on the arc-lamp side of the photometers. It was very satisfactory to us to find that the figures of crater brightness we obtained agreed closly with those of Forrest who had done so much precision work of the first order on this subject. We much regret that the references to his work (with which we are, of course, quite familiar) were omitted from the advance copies of the paper.

In reply to Dr. Haworth, we agree that an indoor method for the measurement of the flux reaching the mirror is the next step which naturally follows the measurement of total flux and experiments are actually in progress for this purpose, using a method working somewhat analogous to that suggested by Mr. Angold. Meanwhile, however, we think that to a first approximation it may be assumed that, at the current densities at which we were working, the crater acts as a perfectly diffusing disc of light, and hence the distribution does not vary sufficiently to introduce serious errors if the total light is considered to be proportional to that which falls on the mirror.

In the measurement of crater brightness at different currents, the size of carbon was not altered, as it was the object of the test to discover the most efficient current density for a given size and type of carbon.

Dr. Haworth's statement that 100 volts would maintain a 150 mm. arc does not express the facts, as this arc length would not be maintainable under ordinary conditions. No doubt as the arc length is increased unduly the candle-power diminishes (see Fig. 5). What it was intended to convey by the statement on page 93 to which he objects, is the fact that no increase of light can be obtained by increase of voltage above about 70 volts. It is understood that Captain Paley-Yorke intends to describe his device in detail and therefore no description of it has been given in the paper. This device was not found *per se* to produce any increase of crater brightness, but in the case of certain carbons, specifically noted in the paper, it enabled the arc to be run at a higher current density than was possible without this device, and hence an increased crater brightness was the indirect result of the use of the control.

We think that Mr. Angold's suggestion for the measurement of the flux falling on the mirror is very practicable and, as stated above, we have already begun work on very similar lines. With regard to the effect of the hollowing of the crater, Mr. Trotter has shown that the polar curve of the arc is practically independent of this for ordinary craters.

In conclusion we should like once more to thank those who in their remarks have helped us by suggesting points for careful consideration in future work and in that now proceeding.

THE SHORT TUNGSTEN FILAMENT AS A SOURCE OF LIGHT AND ELECTRONS.

By G. STEAD, M.A.

(Communicated by Professor Sir J. J. THOMSON.)

(*Paper received* 6 *November*, 1916.)

PRELIMINARY NOTE.

The experiments described in the present paper were carried out in the Cavendish Laboratory during the early part of 1918, and were undertaken in order to provide data for the design of tungsten-filaments for thermionic valves for use in the Royal Navy. The work is now published with the consent of the Admiralty. The section in which the effect of the leads on the candle-power of filaments is considered, has been added (although it has no bearing on thermionic valves) as it is a direct application of the work on end corrections and may be of some interest, especially to lamp manufacturers, since low-voltage lamps with short filaments are much used at the present time.

(I) INTRODUCTION.

Langmuir has investigated very completely* the variation with temperature of certain physical properties of tungsten. His results, however, apply only to filaments which are at a uniform temperature, and consequently do not hold exactly for any real filament, on account of the cooling of the ends by the leads. In electric lamps working at 100–200 volts the filaments are so long that the end corrections are almost negligible, but in thermionic valves short, low-voltage filaments are generally used, and the end corrections become of the utmost importance. The main object of the work described in this paper was to investigate fully these end effects, and to develop methods for the design of filaments which would produce a given electron emission under specified conditions of filament current or voltage. It was found necessary, however, to repeat Langmuir's work on temperature characteristics, as the temperature scale of the optical pyrometer used for the end corrections was not the same as that of Langmuir.

(II) FILAMENT DIAMETERS.

The usual method of determining the diameter of a tungsten filament is to weigh a known length and assume a value for the specific gravity of tungsten. The specific gravity of drawn tungsten is initially about 18, but it increases to 18·5–19·5 after the filament has been aged by heating *in vacuo* to a high temperature (e.g. 2,200° K.). Langmuir therefore assumes 19·0 as a mean value, and this value has been adopted here. The quantity here called the filament diameter is defined by the equation:—

$$d_f = 0{\cdot}008186 \sqrt{w}$$

where w is the weight of the filament in milligrammes per cm. This is based on the value 19·0 for the specific gravity of tungsten.

* *Physical Review*, 1916, ser. 2, vol. 7, p. 302.

Since a metre of tungsten wire of diameter 0·0088 cm. weighs only about 0·12 gramme, it is evident that it is desirable to weigh at least 1 metre and determine the weight to the nearest tenth of a milligramme. Hence, when it is necessary to find the diameter of a short length of filament which has already been used in a valve, the method of weighing is impracticable and a microscope with a micrometer scale in the eyepiece must be used. This is more liable to error than the method of weighing,

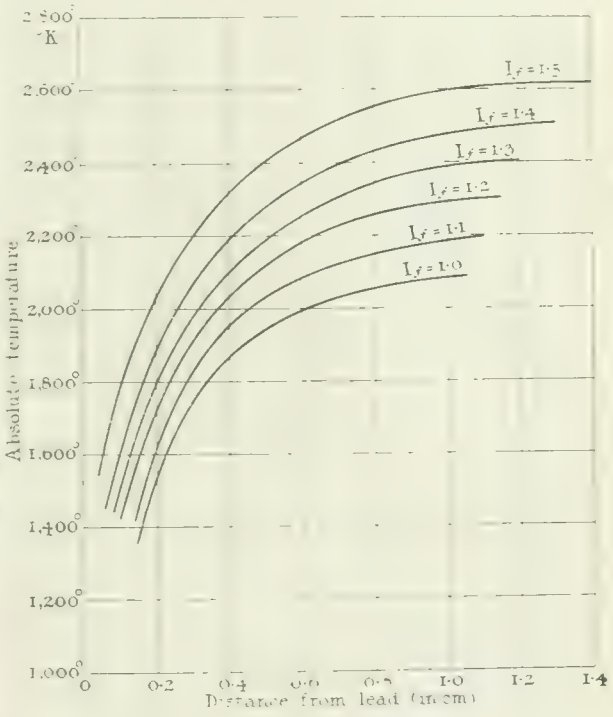


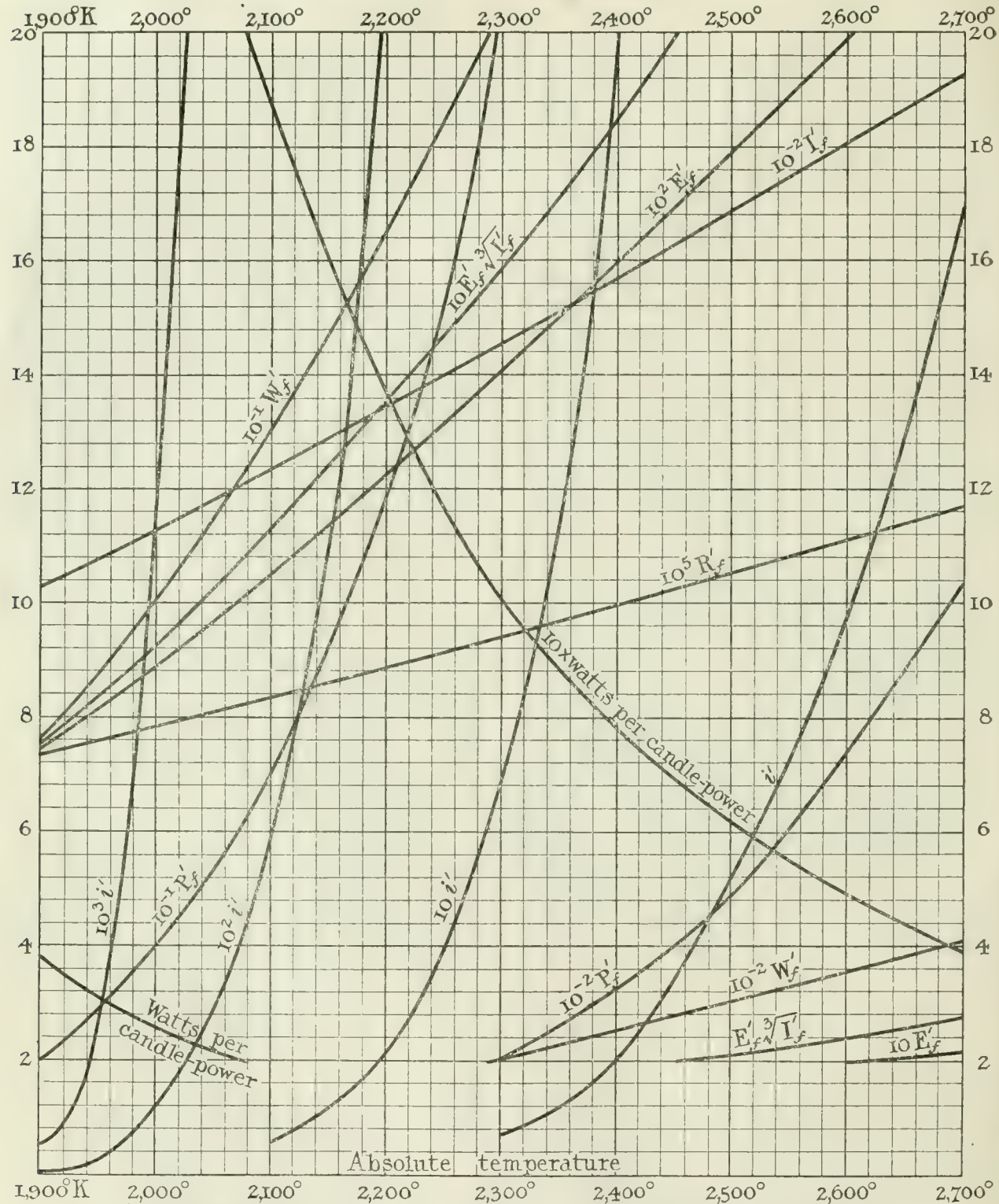
FIG. 1.—Distribution of temperature along tungsten filament of diameter 0·00875 cm.

but the two methods give results in very fair agreement, which is an indication that the value assumed for the specific gravity of tungsten is sensibly correct.

(III) FUNDAMENTAL RELATIONS.

The factors which determine filament voltage, emission (and candle-power) for pure tungsten are :—

(1) Filament length.
(2) Filament diameter.
(3) Filament temperature.
(4) Cooling of the ends of the filament by the leads.



$I'_f = I_f / d_f^{3/2}$ (amp./cm.$^{3/2}$) $\quad E'_f = E_f \sqrt{d_f} / l_f \quad W'_f = W_f / l_f d_f \quad P'_f = P_f / l_f d_f$

$i'' = i / l_f d_f$ (amp./cm.^{2}) $\quad R'_f = R_f d_f^2 / l_f \quad E'_f \sqrt[3]{I'_f} = E_f \sqrt[3]{I_f} / l_f$

d_f and l_f always in centimetres

FIG. 2.—Temperature characteristics of tungsten.

Tungsten is sometimes prepared by the reduction of tungstic oxide to which a small amount (e.g. 1 per cent) of thoria has been added, and both the specific resistance and the electron emission are affected considerably by this addition of thoria. The experiments described below were carried out both for "pure" tungsten and also for 1 per cent thoriated tungsten, but the curves for pure tungsten only are reproduced here and the examples given are also for pure tungsten filaments, except where otherwise stated. All filaments used were supplied by the Osram-Robertson Lamp Works, of Hammersmith.

If I_f, E_f, R_f, W_f, l_f, d_f, P_f, and i denote the filament current, voltage, resistance, watts, length, diameter, candle-power and emission, respectively, then at a given temperature the following expressions are constant :—

$$\frac{I_f}{d_f^{3/2}}\ ;\ \frac{E_f\sqrt{d_f}}{l_f}\ ;\ \frac{R_f d_f^2}{l_f}\ ;\ \frac{W_f}{l_f d_f}\ ;\ \frac{P_f}{l_f d_f}\ ;\ \frac{i}{l_f d_f}\ ;\ \frac{E_f\sqrt[3]{I_f}}{l_f} \quad . \quad (1)$$

(Langmuir, *loc. cit.*) This is only true when the end corrections can be neglected, i.e. it holds for those central portions of filaments which are sensibly at a uniform temperature.

It follows that if two filaments of different diameter work at the same temperature (neglecting end corrections) :—

(*a*) The filament currents are in the ratio of the 3/2 powers of the diameters,
(*b*) the voltages per centimetre are in the inverse ratio of the square roots of the diameters,
(*c*) the resistances per centimetre are in the inverse ratio of the squares of the diameters,
(*d*) the watts per centimetre are proportional to the diameters,
(*e*) the candle-power per centimetre is proportional to the diameter,
(*f*) the emissions per centimetre are proportional to the diameters.

(IV) Experimental Data for Central Portion of Filament.

It is necessary to determine corresponding values of filament current, resistance, emission, temperature, length and diameter. The methods adopted for obtaining these data are described below :—

(1) *Current-voltage data.*—In order to obtain current-voltage data for the central portion of a long filament (i.e. free from end corrections) the filament resistance was measured for a series of temperatures and for filaments of lengths ranging from 1·5 to 15 cm. The resistances were determined by making the filament form one arm of a Wheatstone's bridge. A standard Siemens milliammeter and shunt formed a second arm, and also served to measure the filament current, whilst the remaining arms were taken from a resistance box. The filaments were each mounted in a separate bulb, and the bulbs were highly exhausted by a rotary Gaede pump, followed by charcoal and liquid air. The filaments were aged for 10 hours before the resistance measurements were made, in order to get them into a steady state. The resistance of the leads was measured separately and allowed for.

The various temperatures corresponding to the different currents were determined by sighting a Cambridge optical pyrometer on the middle part of the longest filament, and making corrections for the emissive power of the tungsten and for absorption by the glass of the bulb. Worthing* has determined the emissive powers of tungsten for various temperatures, and his results were used, as the range of wave-lengths transmitted by his optical pyrometer was practically identical with that of the Cambridge pyrometer.

When the resistance for a given temperature is plotted against the filament length, curves are obtained which are straight lines, except close to the origin, where the filaments are so short that the central constant-temperature portion no longer exists. From these curves it is easy to obtain the resistance per centimetre for the central part of a long filament, free from end corrections. The filament currents were measured at the same time, and the filament diameter being known it was therefore possible to plot curves for the various quantities $I_f/d_f^{3/2}$, $E_f\sqrt{d_f}/l_f$, etc. Fig. 2 shows curves obtained in this way for "pure" tungsten filaments supplied by the Osram-Robertson Lamp Works.

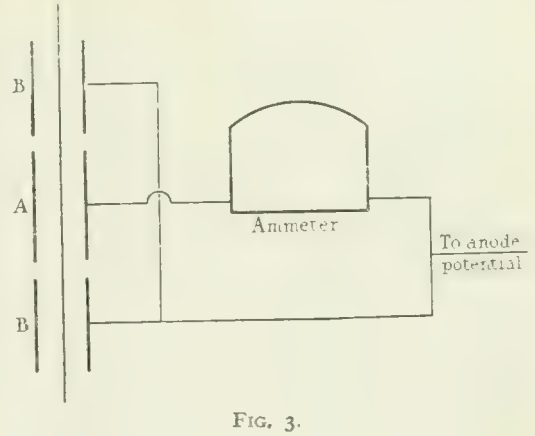


Fig. 3.

(2) *Emission data.*—In order to obtain the necessary emission data a special valve of the type shown in Fig. 3 was made up. The anode, which was of cylindrical form, was made in three portions—a central part A and the two "guard-rings" B, B′, the gaps between A and B being about 0·5 mm. in width. B and B′ were joined together inside the valve, but were insulated from A. Outside the valve A, B and B′ were connected to the positive end of the anode-current battery, and a milliammeter was inserted in such a way as to read the current through A only. The filament was sufficiently long for the part inside A to be at a uniform temperature. Thus the emission current passing through A was the true emission current for a filament at uniform temperature and of length equal to the length of A plus half the width of the gaps between A, B and A, B′. The effect of the cooled ends of the filament was thus eliminated. The distance between the centres of the two gaps was measured to within 2 per cent by a travelling microscope. It amounted to some 11 mm. This was sufficiently accurate for the purpose, as independent observations of the emission for the same filament current differed from one another by several per cent.

* *Physical Review*, 1917, ser. 2, vol. 10, p. 377.

In these experiments the vacuum used was the best that could be obtained by means of charcoal and liquid air. Occluded gas was removed from the bulb by baking for at least an hour at a temperature of about 400° C., and from the electrodes by electron bombardment, whereby the anodes were raised to a bright red heat. The results for "pure" tungsten are shown in Fig. 2, where the function $i/l_f d_f$ is plotted against the temperature.

(3) *Candle-power data.*—For the candle-power data I am indebted to the Director of the Research Laboratories of the General Electric Company, who kindly placed at my disposal the results of some experiments made at the National Physical Laboratory. The data supplied consisted of tables giving (horizontal) candle-powers in terms of filament current and voltage for two filaments, one of which was 20 cm. and the other 4 cm. in length. The temperatures were calculated from the curve for I_f' shown in Fig. 2, and by taking differences the end effects were eliminated. In this way the curve for P_f' shown in Fig. 2 was obtained. This curve can be used only for high-vacuum tungsten lamps, and does not apply to gas-filled lamps.

V. Method of Determining End Corrections.

For a filament which is only a few centimetres in length the cooling due to the leads has a very large effect on the filament voltage, emission, etc. It was necessary first to determine by experiment the distribution of temperature along a filament in the neighbourhood of a lead. It was desirable, after this, to find, if possible, some simple method of deducing the temperature distribution along any other filament of different diameter. Finally the results must be presented in such a form as to be easily applied to the practical design of filaments.

(1) *Experimental method.*—The temperature distribution along a filament of diameter 0·00875 cm. was determined by means of the Cambridge pyrometer, which was mounted on a cathetometer in front of a bulb containing a long "hair-pin" filament, the limbs of the filament being vertical. A diaphragm was attached to the front of the pyrometer, so that only a short length of filament could be seen at once. In this way it was possible to measure the temperature at a series of points along the filament and so obtain the curves reproduced in Fig. 1. Thus the temperature distribution along a filament of given diameter was determined for a series of maximum temperatures.

(2) *Application to filaments of different diameters.*—The surface temperature of a tungsten filament has been investigated by Worthing,* partly experimentally and partly theoretically. He finds that the following expression represents the distribution of temperature very fairly :—

$$T = T_m \left[1 - e^{-\mu(\lambda + \lambda_0)}\right]^n \quad . \quad . \quad . \quad . \quad (2)$$

Here T° K. is the temperature at a point distant λ cm. from the cooling junction, T_m K. is the temperature at a point where the cooling due to the leads is negligible, and μ, λ_0, and n are constants. λ_0 depends on the diameter and thermal conductivity of the leads, but has not much effect, except close to the leads. For ordinary lamp leads it may be taken as 0·25 cm., and for stout leads suitable for 4-ampere filaments as 0·20 cm. The constant μ varies inversely as the square root of the diameter of the filament. Worthing gives the value 3·8 for a filament of diameter 0·01045 cm., and this result has been confirmed.

If λ and λ' are the distances from the cooling junction of points at the same temperature (T) on filaments of diameters d_f and d_f', whose central portions are at the same temperature (T_m), it follows from (2) that

$$1 - e^{-\mu(\lambda + \lambda_0)} = 1 - e^{-\mu'(\lambda' + \lambda_0)}$$

i.e.

$$\frac{\lambda' + \lambda_0}{\lambda + \lambda_0} = \frac{\mu}{\mu'} = \sqrt{\frac{d_f'}{d_f}} \quad . \quad . \quad . \quad . \quad . \quad (3)$$

Hence, when the temperature distribution along any one filament is known, that along another filament of different diameter, but working at the same maximum temperature (T_m); is easily calculated.

(3) *Length of the end* (λ_n).—The temperature-distribution curves shown in Fig. 1 are each continued up to the point at which the temperature has become 99·9 per cent of the temperature of the central portion. The distance from the lead at which this occurs will be called the length of the end (λ_n). The value of the length of the end is of course chosen arbitrarily. In Fig. 4 the quantity $(\lambda_n + \lambda_0)/\sqrt{d_f}$ is plotted against the temperature, λ_0 being taken as 0·25 cm. To determine the length of the end for a given filament at a given temperature, it is only necessary to look up the value of $(\lambda_n + \lambda_0)/\sqrt{d_f}$, multiply by the appropriate $\sqrt{d_f}$, and subtract 0·25 cm. from the result. These curves may be used even when the leads are so stout that $\lambda_0 = 0{\cdot}20$ cm., as the slight difference in λ_0 does not have any appreciable effect on the length of the end.

(4) *Voltage in the end* (V_n).—By combining the results shown in Fig. 1 with those in Fig. 2, curves can be drawn which give the relation between the voltage per centimetre $\left(\frac{dE}{d\lambda}\right)$ and the distance from the lead. By finding the areas under these curves the quantity here called the voltage in the end (E_n) was obtained. In Fig. 4 the voltage in the end is plotted against the temperature (T_m) of the central portion of the filament.

By Equation (3) we have :—

$$\frac{\lambda' + \lambda_0}{\lambda + \lambda_0} = \sqrt{\frac{d_f'}{d_f}} = k, \text{ where } k \text{ is a constant.}$$

Hence, differentiating, $\frac{d\lambda'}{d\lambda} = k$.

Also, when $\lambda = \lambda_n$, $\lambda' = \lambda_n'$, and
when $\lambda = 0$, $\lambda' = (k - 1)\lambda_0$.

Thus,

$$E_n = \int_0^{\lambda_n} \left(\frac{dE}{d\lambda}\right) d\lambda = \int_{(k-1)\lambda_0}^{\lambda_n'} k \left(\frac{dE'}{d\lambda'}\right) \frac{d\lambda'}{k}$$

$$= \int_0^{\lambda_n'} \left(\frac{dE'}{d\lambda'}\right) d\lambda' - \int_0^{(k-1)\lambda_0} \left(\frac{dE'}{d\lambda'}\right) d\lambda'$$

$$= E_n' - \int_0^{(k-1)\lambda_0} \left(\frac{dE'}{d\lambda'}\right) d\lambda$$

* *Physical Review*, 1914, ser. 2, vol. 4, p. 524.

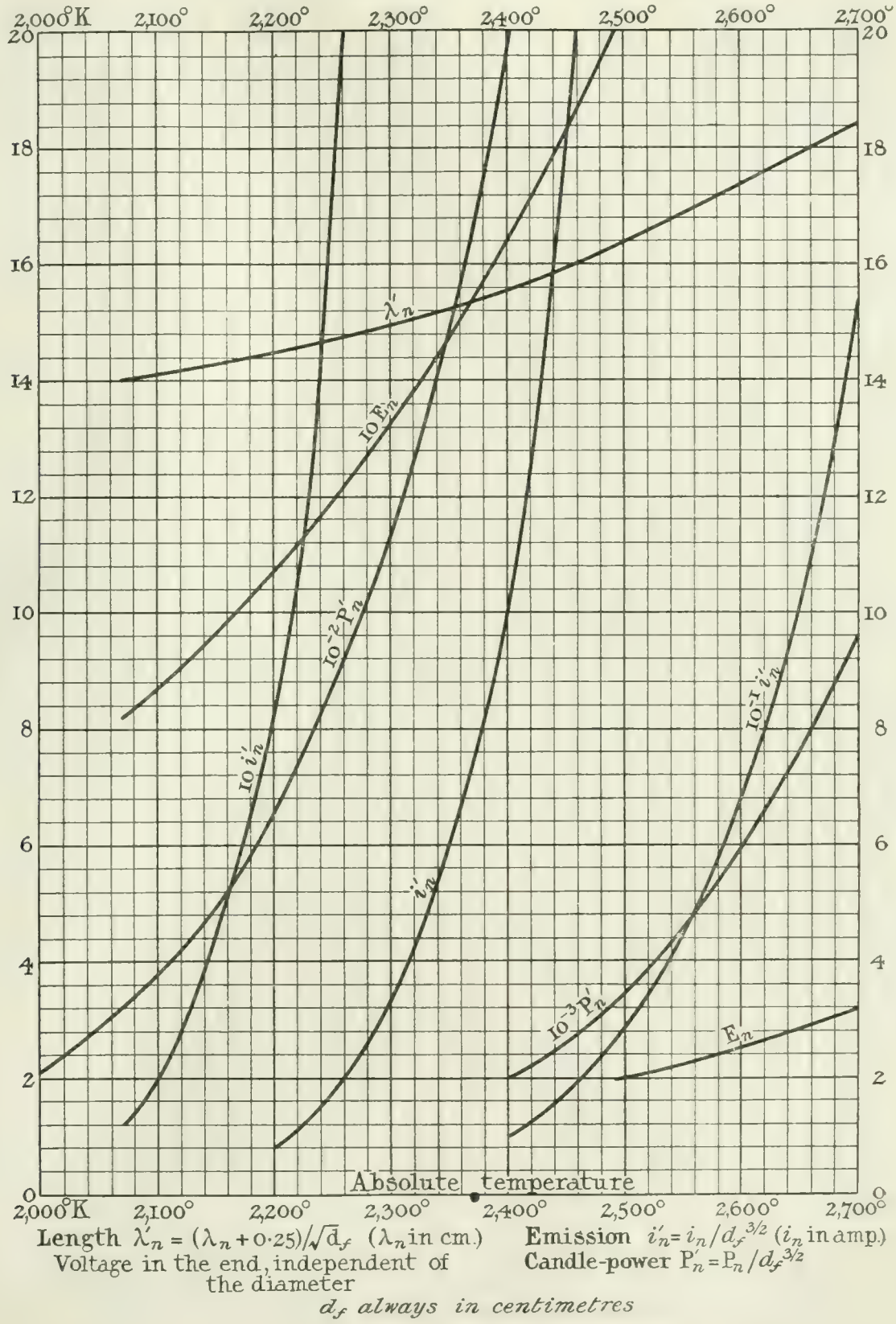


FIG. 4.—End-correction curves for tungsten filaments.

Now, in practice $\int_0^{(k-1)\lambda_0} \left(\frac{d\,E'}{d\,\lambda'}\right) d\,\lambda'$ is very small compared with the filament voltage, except in the case when the filament is very short, very thin, and running at a very high temperature. Hence, it is usually sufficiently accurate to write $E_n = E'_n$. The value of $\int_0^{k-1)\lambda_0} \left(\frac{d\,E'}{d\,\lambda'}\right) d\,\lambda'$ may be estimated as follows :—

Case of a filament of diameter 0·0200 *cm., running at a maximum temperature of* 2,600° *K.* ($I_f = 5{\cdot}2$ *amperes.*)

If Equation (2) holds right up to the lead we have

$T = 1{,}100°$ K., when $\lambda = (k-1)\lambda_0$, and
$T = 600°$ K., when $\lambda = 0$.

The values of $\frac{d\,E'}{d\,\lambda'}$ corresponding to these temperatures are 0·113 and 0·032 respectively. The mean of these is 0·072. Also $(k-1)\lambda_0 = 0{\cdot}13$ cm.

Hence, approximately

$$\int_0^{(k-1)\lambda_0} \left(\frac{d\,E'}{d\,\lambda'}\right) d\,\lambda' = 0{\cdot}072 \times 0{\cdot}13 = 0{\cdot}0094.$$

Hence, for both leads, the error amounts to 0·019 volt.

Moreover, since in all probability the temperature at points near the lead is smaller than that given by Equation (2), the above estimate may be taken to represent an upper limit for the error.

It may be shown in the same way that, for a filament of diameter 0·0504 cm. running at 2,600° K. (i.e. $I_f = 21$ amperes), the error due to the two leads is not greater than 0·017 volt.

When d_f is taken much smaller than the standard 0·00875 cm. on which the original observations were made, the error begins to be larger, owing to the rise of $\frac{d\,E'}{d\,\lambda'}$. For $d_f = 0{\cdot}0035$ cm. and $T_m = 2{,}600°$ K. ($I_f = 0{\cdot}38$ ampere) the error for the two ends amounts to 0·12 volt. It is worth noticing, however, that the voltage per centimetre in the central portion is 3·4 in this case, and that the error in length in mounting a filament in its supports is about 0·5 mm. The voltage corresponding to the half millimetre is 0·17 and is therefore greater than the error in the voltage in the end.

For a filament as fine as 0·00175 cm., running at 2,600° K., ($I_f = 0{\cdot}134$ ampere) the error ceases to be negligible, as it is of the order of 0·4 volt, whereas the voltage corresponding to 0·5 mm. of the central part of the filament is 0·24.

The temperature (2,600° K.) chosen in the above examples corresponds to an efficiency of about 0·5 watt per candle-power. The value of $\int_0^{(k-1)\lambda_0} \left(\frac{d\,E'}{d\,\lambda'}\right) d\,\lambda'$ diminishes rapidly as the temperature is lowered, so that over a wide range of filament diameters and temperatures it is sufficiently accurate to put $E_n = E'_n$. Thus, with the limitation noted above, the voltage in the end is independent of the filament diameter, for a given temperature of the central portion. In Fig. 4 the voltage in the end is plotted against the temperature of the central portion of the filament.*

(5) *Emission from the end* (i_n).—By a method exactly similar to that used for the voltage in the end it is possible to determine the emission from the end (i_n). Using the same notation as before, we have :—

$$i_n = \int_0^{\lambda_n} \left(\frac{d\,i}{d\,\lambda}\right) d\,\lambda = \int_{(k-1)\lambda_0}^{\lambda'_n} \frac{1}{k^2}\left(\frac{d\,i'}{d\,\lambda'}\right) \frac{d\,\lambda'}{k}$$

$$= \frac{1}{k^3}\int_0^{\lambda'_n} \left(\frac{d\,i'}{d\,\lambda'}\right) d\,\lambda' - \frac{1}{k^3}\int_0^{(k-1)\lambda_0} \left(\frac{d\,i'}{d\,\lambda'}\right) d\,\lambda'$$

$$= \frac{i'_n}{k^3} \text{ approximately.}$$

Thus $\frac{i_n}{d_f^{3/2}} = \frac{i'_n}{d'^{3/2}_f} =$ a constant.

The error in neglecting $\frac{1}{k^3}\int_0^{(k-1)\lambda_0} \left(\frac{d\,i'}{d\,\lambda'}\right) d\,\lambda'$ is very much smaller than the corresponding error in the voltage in the end considered in the preceding paragraph, as, for all temperatures below 1,900° K., the value of $\frac{d\,i}{d\,\lambda}$ is entirely negligible, so far as thermionic valves are concerned.

(6) *Candle-power of the end* (P_n).—The candle-power per centimetre in the central part of the filament is directly proportional to the filament diameter. Hence, by an exactly similar proof to the one used above for emission, it can be shown that the candle-power of the end is proportional to the 3/2 power of the filament diameter. In Fig. 4 the quantity $P_n/d_f^{3/2}$ is plotted against the temperature of the central portion.

(VI) Procedure for Designing a Filament to Produce a Given Electron Emission when the Overall Voltage is Given and the Filament Diameter is Provisionally Chosen.†

The procedure for designing a filament to produce a given emission for a given overall voltage may be conveniently summarized as follows :—

(*a*) Assume a probable value for the temperature of the central portion of the filament.

(*b*) Subtract twice the voltage in the end from the overall voltage. (It is assumed that the filament is sufficiently long for the temperature of the central portion to be unaffected by the leads. The case when this is no longer true is considered below.)

* Experience showed that, whilst for thoriated tungsten there was good agreement between calculated and observed values of the filament voltage, for "pure" tungsten there seemed to be a small error in E_n. This error was determined by subsequent experiments, and the revised curve for E_n is here shown.

† In choosing a filament diameter an allowance of 3 per cent should be made for filament wastage during evacuation.

(*c*) To obtain the length of the central part of the filament (λ_m) find the voltage per cm. corresponding to the given temperature (Fig. 2) and divide it into the result obtained in (*b*).

(*d*) Find twice the length of the end (Fig. 4) and add it to the result obtained in (*c*). This gives the total length of the filament (l_f).

(*e*) To obtain the emission from the central portion (i_m), determine the emission per cm. (Fig. 2) and multiply it by the length of the central portion of the filament.

(*f*) Find the emission from the end (i_n, Fig. 4) and multiply by two. Add to the result of (*e*) to obtain the total emission (i).

The above calculations may be made for various temperatures of the central part of the filament, and the filament length may then be plotted against the temperature. In this way the particular length (and temperature) which gives the required emission can be found. The filament current may then be obtained from the curve for $I_f/d_f^{3/2}$ in Fig. 2. In practice the curves prove to be fairly straight over a range of 50° K. or so. Hence it usually suffices to calculate the emission for two lengths, and interpolate. If the range of interpolation is more than about 50° K., better results are obtained by interpolating logarithms of the total emission, as shown in the examples given below. Logarithmic interpolation gives results of very fair accuracy even over a range as great as 200° K., though it is seldom necessary in practice to interpolate over so wide a range.

Similar calculations may be made for any filament diameter. If the diameter is large the required filament temperature is lower than if the diameter is small. On the other hand, a large diameter involves a large filament current. Thus, for a given design, the filament diameter is limited in one direction by the rise of filament watts, and in the other direction by the rise of temperature and consequent shortening of life.

Example I.—Design of 6-volt, 50-ma. filament, of diameter 0·0088 cm.

(*a*) Assume $T_m = 2{,}450°$ K.

$2E_n = 3{\cdot}65$ $\quad 2i_n = 29{\cdot}6$ $\quad \sqrt{d_f} = 9{\cdot}39 \times 10^{-2}$

$\therefore E_m = 2{\cdot}35$ $\quad i_m = 30{\cdot}6$ $\quad d_f^{3/2} = 8{\cdot}23 \times 10^{-4}$

$2\lambda_n = 2{\cdot}50$ $\quad \therefore i = 69{\cdot}2$ ma. $\quad E_f/l_f = 1{\cdot}805$

$\lambda_m = 1{\cdot}30$ $\quad I_f/l_f = 30{\cdot}4$

$\therefore l_f = 3{\cdot}80$ cm.

(*b*) Assume $T_m = 2{,}420°$ K.

Then $l_f = 3{\cdot}93$ cm., and $i = 54{\cdot}5$ ma.

(*c*) $T_m = 2{,}400°$ K. $\quad l_f = 4{\cdot}01$ cm. $\quad i = 44{\cdot}5$ ma.

(*d*) $T_m = 2{,}350°$ K. $\quad l_f = 4{\cdot}24$ cm. $\quad i = 29{\cdot}5$ ma.

Interpolation between 2,400° K. and 2,420° K. gives

$l_f = 3{\cdot}97$ cm. $\quad T_m = 2{,}411°$ K.

Interpolation between 2,350° K. and 2,450° K. gives

$l_f = 4{\cdot}02$ cm. $\quad T_m = 2{,}402°$ K.

Logarithmic interpolation between 2,350° K. and 2,450° K. gives

$l_f = 3{\cdot}97$ cm. $\quad T_m = 2{,}412°$ K. $\quad I_f = 1{\cdot}30$ amperes.

The advantage of logarithmic interpolation for the wider range is clear.

Example 2.—Design of 4-volt, 10-ma. filament of diameter 0·0058 cm.

T_n	$2E_n$	E_m	$2\lambda_n$	λ_m	l_f	$2i_n$	i_m	i	E_f/l_f	I_f/l_f
2,350° K.	2·96	1·04	1·82	0·53	2·35	5·30	3·53	8·83	1·98	0·72
2,300 K.	3·22	0·78	1·86	0·38	2·24	8·02	3·81	11·83	2·07	10·1

Interpolation gives $l_f = 2{\cdot}31$ cm., $T_m = 2{,}366°$ K., $I_f = 0{\cdot}676$ ampere.

Example 3.—Design of 10-volt, 250-ma. filament of diameter 0·020 cm.

T_n	$2E_n$	E_m	$2\lambda_n$	λ_m	l_f	$2i_n$	i_m	i	E_f/l_f	I_f/l_f
2,350° K.	2·96	7·04	3·80	6·61	10·41	34·1	154·9	189·0	1·063	23·4
2,400° K.	3·28	0·72	3·92	5·94	0·86	56·8	237·5	294·3	1·134	40·0

Interpolation gives $l_f = 10{\cdot}1$ cm., $T_m = 2{,}379°$ K., $I_f = 4{\cdot}39$ amperes.

(VII) Case in which the "Ends" Overlap.

So far it has been assumed that twice the voltage in the end is less than the required overall voltage. When the filament voltage is 4, or less, it may easily happen that this is not the case, and the matter requires further consideration.

Equation (2) shows that, at a given distance from a cooling junction, the temperature is given by

$T = T_m(1-a)^n$, where $a = e^{-(\lambda - \lambda_0)}$

$= T_m(1 - na)$, if a is small.

Hence, at a point where both leads produce an appreciable cooling, the temperature is given by

$$T = T_m (1 - a)^n (1 - b)^n$$
$$= T_m [1 - n (a + b)] \text{ if } a \text{ and } b \text{ are both small} \quad (4)$$

Thus, in Fig. 5, if G N represents the temperature at a point G in the filament when the leads have no effect, H N the temperature when one lead is effective, and J N the temperature when the other lead is effective, then K N will represent the temperature when both leads are effective, where J K = G H. Thus, the distribution of temperature along a filament is easily plotted when the cooling effect due to one lead is known. (This method clearly does not apply when the overlapping of the ends is very large, but such a case is unlikely to occur in practice.) When the temperature distribution is known it is possible to plot $\frac{dE}{d\lambda}$ and $\frac{di}{d\lambda}$ against the distance from a lead, and by finding the areas under these curves E_f and i are obtained. The process is, however, very tedious, and involves a large amount of trial and error, as it is

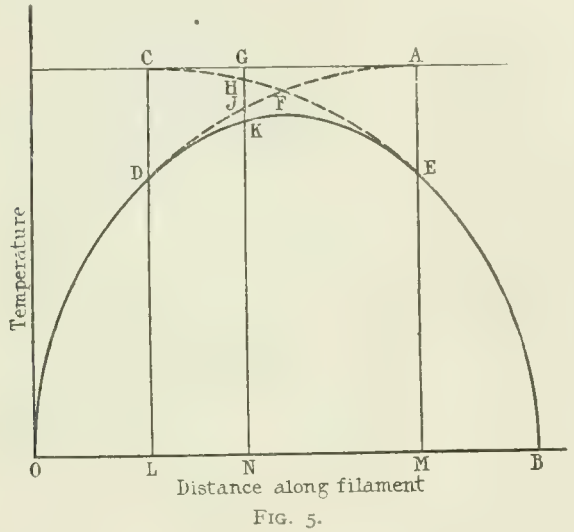


FIG. 5.

necessary to start from a given filament length instead of a given voltage. Fortunately, it is unnecessary if the amount of overlapping of the leads is small. This may be seen as follows :—

Let O A and B C (Fig. 5) represent the temperature distributions due to the ends considered separately, and O D E B the actual distribution due to both ends. Then, since G H = J K, it follows that the area C A F is equal to the area F E D. Hence

$$\text{O A M} + \text{B C L} - \text{C A M L} = \text{O F B} + \text{C F A M L} - \text{C A M L}$$
$$= \text{O F B} - \text{C A F}$$
$$= \text{O F B} - \text{F E D}$$
$$= \text{O D E B}$$

Thus, area O D E B = 2 area O A M — area C A M L
= 2 × (area of end) — C A M L

and length O B = 2 O M — L M

i.e. length of filament = 2 × (length of end) — L M.

Now, if the voltage per centimetre were proportional to the temperature, it is clear that the filament voltage would be proportional to the area O D E B, and the voltage in the end proportional to the area O A M. Hence, in this case,

Filament voltage
= 2 × (voltage in the end) — voltage for length L M.

Thus the filament design could be proceeded with in the usual manner except that a negative quantity would result from the subtraction of twice the voltage in the end from the overall voltage, and so the "length of the middle" (λ_m) would have to be subtracted from twice the length of the end.

Actually the voltage per centimetre is not proportional to the temperature of the filament, but the relation is very nearly linear over quite considerable ranges, and so the method is legitimate unless the overlapping is considerable. Thus, take the case of a filament of diameter 0·00875 cm. At 2,200° K. the value of E_f/l_f is 1·310, at 2,300° K. it is 1·507, and at 2,400° K. it is 1·709. 1·507 — 1·310 = 0·197, and 1·709 — 1·507 = 0·202. It is clear from this that quite a large amount of overlapping must occur before the filament voltage calculated in this way is appreciably in error. In the above example an overlap of about 1 cm. would be required to produce the effect considered.

Similar considerations apply in the case of emission, but, as the curve for i/l_f plotted against the temperature is much less nearly straight than the E_f/l_f curve, the error for a given overlap is considerably greater. For the filament considered above the value of i/l_f at 2,280° K. is 4·82, at 2,300° K. it is 5·98, and at 2,320° K. it is 7·24. The first difference is 1·16 and the second 1·26. The overlap permissible for this order of accuracy is about 0·5 cm.

Example.—1 per cent thoriated tungsten filament, of length 2·0 cm. and diameter 0·00875 cm., traversed by a current of 1·3 amperes.

$2\lambda_n = 2{\cdot}42$ cm.	$i/l_f = 22{\cdot}8$.
$\lambda_m = -0{\cdot}42$ cm.	$2i_n = 19{\cdot}64$ ma.
$E_f/l_f = 2{\cdot}025$.	$i_m = 09{\cdot}6$ ma.
$2E_n = 3{\cdot}54$ volts.	$i = 10{\cdot}04$ ma.
$E_m = -0{\cdot}86$ volts.	
$E_f = 2{\cdot}68$ volts.	
Correct filament voltage	$= 2{\cdot}66$.
Correct emission	$= 10{\cdot}19$ ma.

(VIII) IMPORTANCE OF COOLING DUE TO LEADS WHEN LENGTH OF FILAMENT IS SMALL.

It will now be clear that the cooling effect due to the leads is of great importance in the case of short filaments. Thus in Example 1, Section VI, above, if the leads produced no cooling the overall voltage required to produce the given filament current would be 6·88 instead of 6, whilst the total emission would be 80 ma. instead of 50 ma. The great influence which the cooling due to the leads has on the total electron emission is well brought out in Fig. 6, where the emission per cm. is plotted against the distance from a lead, for a filament of diameter 0·0058 cm. For the upper curve the total emission is 92 ma. If the leads produced no cooling the total emission would be about 150 ma. It is evident that most of the emission current is due to the middle centi-

metre of the filament, the remaining 1·4 cm. producing but little more than 25 per cent of the total emission.

(IX) Effect of Cooling due to Leads on Candle-power of Electric Lamps.

It is clear that the efficiency of electric lamps must be diminished by the cooling of the ends of the filaments

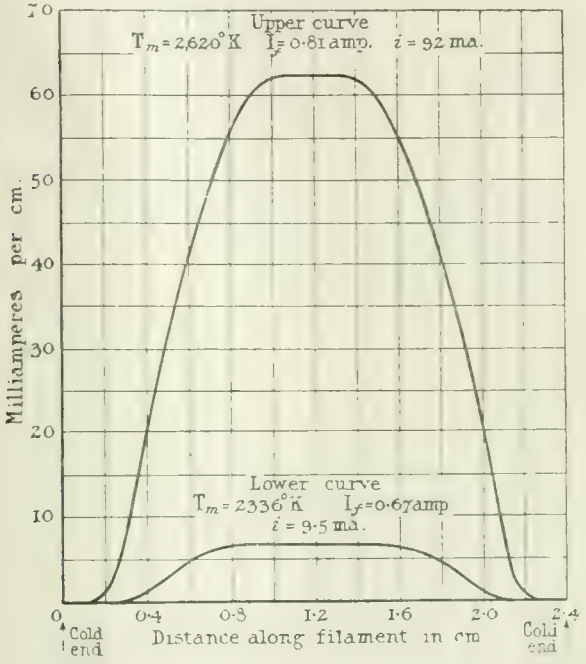


Fig. 6.—Effect of cooling due to leads on emission from tungsten filament of length 2·4 cm., diameter 0.0058 cm.

by the leads, but in high-voltage lamps the end-effects are practically negligible owing to the great length and small diameter of the filaments. For low-voltage lamps this

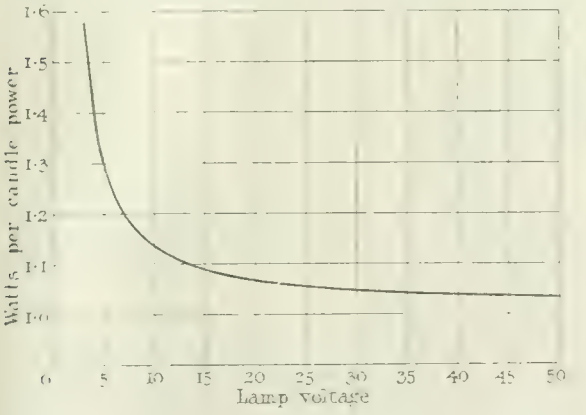


Fig. 7.—Relation between efficiency and voltage for 16-watt tungsten filaments whose central portions are at a temperature of 2,300° K

is no longer true and the end corrections become of importance. The candle-power of any filament can be calculated from the curves shown in Figs. 2 and 4, in a manner exactly the same as that already described for determining electron emission. In this way it is easy to find how the efficiency varies under different conditions. The following will serve as illustrations:—

Example (1).—The curve reproduced in Fig. 7 shows the variation of efficiency with voltage when the temperature of the central portion of the filament is kept constant. The calculations have been made for a 16-watt filament running at a maximum temperature of 2,300° K. The ordinates show watts per candle-power, and the abscissæ overall voltage. The curve shows clearly the rapid rise of watts per candle-power when the lamp voltage is less than about 10 volts.

Example (2).—The case of a 16 candle-power 16-watt lamp is taken as the second illustration. The curves reproduced in Fig. 8 show the filament length, diameter, and maximum temperature as functions of the overall voltage. It will be seen that in order to keep the efficiency at 1 watt per candle-power the temperature of the central portion of the filament has to be increased to a large extent in low-voltage lamps. This is, of course, due to the fact that in such lamps most of the light comes from a short, hot spot near the centre of the filament. The presence of the hot spot naturally tends to shorten the life of the filament.

(X) Approximate Method for More Rapid Design of Filaments.

It has been found that the following approximate method of filament design gives results of very fair accuracy in the cases most likely to occur in practice, i.e. for filament temperatures from 2,000° K. to 2,500° K., and for filament diameters from 0·0035 cm. to 0·012 cm. (With the modification noted below it can be used for still larger filament diameters, as illustrated in Example 3.) It is considerably quicker than the exact method given above, and is useful in preliminary work.

The object of the method is, first, to find the overall voltage which would be necessary if the whole filament were as hot as the middle part. The filament length can then be found at once from the $E_f \sqrt{d_f}/l_f$ curve (Fig. 2). Next the length is found of a filament which gives the same emission as the actual filament, and whose temperature is everywhere the same as that of the central portion of the actual filament. The emission can then be found from the $i/l_f d_f$ curve (Fig. 2). The procedure may be summarized as follows:—

Filament-length.

(*a*) Subtract 350 from the absolute temperature of the central portion of the filament, multiply the result by 4 and divide by 10,000.

(*b*) Subtract filament diameter (in centimetres) from 0·0088 cm. and multiply result by 100.

(*c*) Subtract (*b*) from (*a*) and add result to required overall voltage.

(*d*) Find E_f/l_f from Fig. 2 and divide it into result of (*c*). This gives required filament length.

Emission.

(*e*) Multiply the length of the end (Fig. 4) by 1·20, and subtract the result from the length of the filament found in (*d*).

Let result be l'.

(f) Find emission corresponding to l' by means of $i/l, d_f$ curve in Fig. 2.

Example 1.—4-volt filament of diameter 0·0058 cm. Temperature of central portion 2,390° K.

2,390	0·0088	$4·816 - 0·30 = 4·516$
350	0·0058	$E_f/l_f = 2·073$
2,040	$0·0030 \times 100 = 0·30$	$\therefore l_f = \frac{4·516}{2·073} = 2·18$ cm.
4		(Correct value = 2·20 cm.)
8,160		

$\lambda_n = 0·92$ cm. $0·92 \times 1·2 = 1·10$.
$2·18 - 1·10 = 1·08$, $i/l_f = 10·3$, $\therefore i = 10·3 \times 1·08 = 11·1$ ma.
(Correct value = 11·6 ma.)

Example 2.—6-volt filament of diameter 0·0100 cm. Temperature of central portion 2,500° K.

2,500	0·0088	$6·86 - (-0·12) = 6·98$
350	0·0100	$E_f/l_f = 1·79$
2,150	$-0·0012 \times 100$	$\therefore l_f = 3·90$ cm.
8,600		(Correct value = 3·89 cm.)

$\lambda_n = 1·39$. $1·39 \times 1·2 = 1·67$.
$3·90 - 1·67 = 2·23$, $i/l_f = 52·2$, $i = 116·3$ ma.
(Correct value = 115·8 ma.)

As mentioned above, the approximate method is satisfactory up to a diameter of about 0·0120 cm. For filaments thicker than this the correction becomes nearly independent of the diameter, and very fair results are obtained for filaments larger than 0·0120 cm. by employing the diameter correction appropriate to a 0·0120 cm. filament, i.e. $0·0088 - 0·0120 = -0·32$ should be subtracted from the overall voltage; in other words, 0·32 should be added to it. The following example illustrates this:—

Example 3.—6-volt filament of diameter 0·0250 cm. Temperature of central portion 2,400° K.

2,400	$6·82 + 0·32 = 7·14$.	$E_f'/l_f = 1·012$.
350	$l_f = \frac{7·14}{1·012} = 7·05$ cm.	
2,050	(Correct value 7·09 cm.)	
8,200		

$\lambda_n = 2·21$. $2·21 \times 1·2 = 2·65$.
$7·05 - 2·65 = 4·40$, $i/l_f = 50·0$, $= 220$ ma.
(Correct value = 213 ma.)

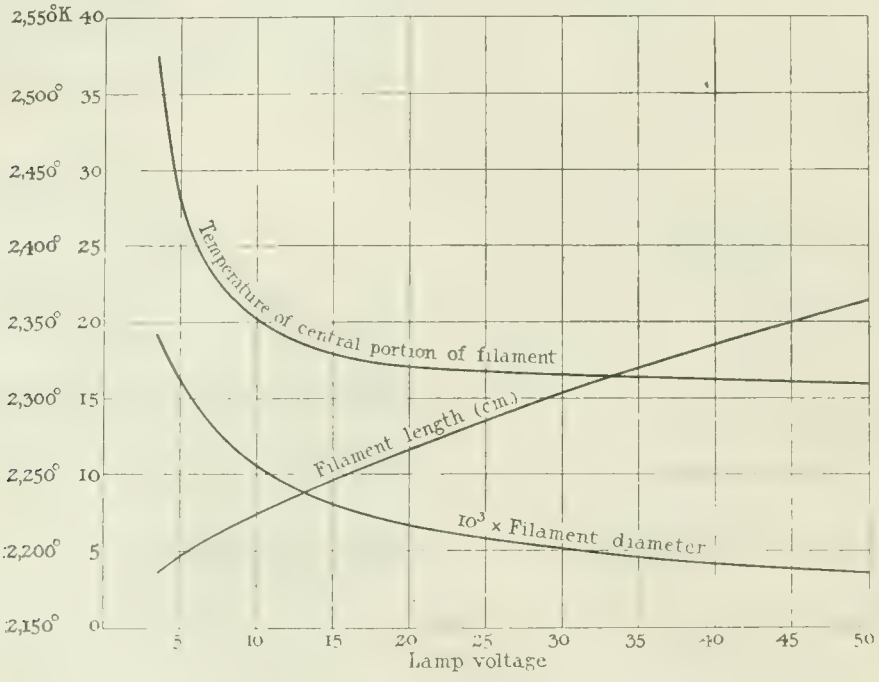


FIG. 8.—Design for 16 c.p. 16-watt lamp for various voltages.
(*The filament diameter is in centimetres.*)

(XI) SUMMARY.

The principal matters dealt with in the paper may be summarized as follows:—

(1) A determination has been made of certain characteristics of tungsten as functions of the temperature. These characteristics include filament resistance, voltage, electron emission, etc.

(2) The distribution of temperature along a tungsten filament in the neighbourhood of a lead has been determined by means of an optical pyrometer mounted on a cathetometer. This has been done for a series of maximum temperatures, and it is shown how to calculate from these observations the distribution of temperature along a tungsten filament of any diameter.

(3) By combining the results of (1) and (2) end-correction curves have been obtained for voltage, electron emission, etc.

(4) Methods, based on (1) and (3), are then described for the design of filaments to give any desired electron emission for a given overall voltage. The curves given

enable similar methods to be developed for the design of filaments to satisfy a variety of other conditions, e.g. filaments in which a specified filament current will produce a given emission, etc.

(5) A discussion is given of the effect of the cooling due to the leads on the candle-powers of short, low-voltage incandescent lamp filaments. It is shown that in such cases the greater part of the light comes from a small, intensely hot spot in the middle of the filament, and that consequently, for a given luminous efficiency, the life of the lamp is shorter than that of a high-voltage lamp with a long filament.

In conclusion, I wish to express my best thanks to Professor Sir J. J. Thomson for his kindness in placing at my disposal the facilities afforded by the Cavendish Laboratory.

ADDRESS TO THE STUDENTS' SECTION.

By A. P. Trotter, Member.

(Address delivered 21 November, 1919.)

It is not easy for one who is approaching the end of his professional career to address those who are entering on their life's work. The lessons to be learned from the experience of others are of little importance compared with the knowledge which you will gain in acquiring your own experience, and the experience of one who for more than 20 years was a government official is of little interest to you.

Looking back, as I can do, over the history of electrical engineering, it seems impossible that the conditions which surrounded it, and from which it eventually emerged, and the difficulties which were opposed to it, but which were overcome, can ever occur again.

Looking at the present, we all feel unconsciously, even if we do not put it into words, the great gulf that the War has fixed between 1914 and 1919. The future, we can none of us at this moment hope to gauge, but at the back of everything that we do lies a great regret for all the comrades who once faced life with us. Sixty-six of the Students of this Institution were killed in the War, or died of wounds, or as the result of service in the Forces, a number amounting to nearly one half of the whole Roll of Honour of the Institution.

It is difficult to realize that more than a year has passed since the end of the War. So far from a settling down of regular conditions of life and work, almost every day brings further complications in industrial matters. You will encounter obstacles which I cannot foresee, and surmount them by methods which are now unknown, and you will assuredly win the rewards that you seek if you are wise in measuring your success.

Nearly all of you, I suppose, are entering the profession of electrical engineering in order to make a living. Some of you are born engineers who would be happy in no other calling, and you will measure your success by the achievement of engineering work. Some are scientific at heart, and look on electrical engineering as one of the most scientific branches of industry. You will be rewarded by the part you play in researches and discoveries. And there may be a few who have been told that electricity is in its infancy, and that it is the coming thing. But that is an old tale that has been told for nearly 40 years. Some of you will only measure your success by the money you make. You will deserve it. But do not judge of the success of others by the same measure. They may have ideals of which money-making men have no conception.

A few of you perhaps have already developed strong inclinations towards certain subjects and feel that you can help to develop and to make your mark in them, but most will take advantage of opportunities that offer, not because they are paths of least resistance, but for the mere fact and sufficient reason that the opportunities are there. When I took part in the enlistment of the Engineers of the Royal Naval Division I interviewed a large number of young men and others who professed that they were young enough. They were not mere average engineers, but a particularly keen and capable lot. Each one gave me a short account of his career, and I was struck by the number of different jobs that they had passed through. They had stayed for an average of about $3\frac{1}{2}$ years with one employer after another. These rolling stones gave moss no chance to grow on them, but the diversity of experience which they gathered was large, though each step must have been a small one as far as rise of pay was concerned.

Another thing which struck me was the length of time which a student in Scotland spends at college. Courses of five years, and sometimes seven, including evening classes, is a very different thing from the usual two years, or less usual three years of the English student. I would strongly recommend those who can manage it to remain three if not four years at college. It is true that our colleges are overcrowded at present and there may not appear to be much inducement for a student to stay, but I feel sure that in most cases the postponement of the first year's earnings will be amply make good afterwards. I do not recommend early specialization, though the last year at college should include research work, and this must of necessity be

on one or more special subjects. The professor at a college has to keep all his subjects going, and reminds me of a juggler who keeps five or six balls in the air at once. It looks so easy. It is not difficult, to the man who does it, but he has acquired facility by practice.

In later life most engineers specialize; some are forced by their own strong inclinations, others have opportunities thrust upon them. One of the subjects which is so prominent at a technical college is dynamo design. It is eminently a subject for textbooks, lectures, blackboard work, and examination papers. It is a subject with which nearly every electrical engineer must have some acquaintance, and yet, probably, not 3 per cent of the members of the Institution are engaged in dynamo design. The knowledge of this subject which is needed in after life is like the general knowledge of veterinary science which is useful to a farmer. Although he may not know the meaning of the words physiology, pathology and diagnosis, he understands how to keep his stock in health and to recognize and to some extent to treat disease or accidental injuries.

Forty years ago I studied the steam engine and the setting of slide valves, and when I could use Zeuner's diagram, and knew several valve motions I imagined that there was not much more to be learned in that direction. Then came the Corliss and other trip valves and the high-speed Tower spherical engine, and the Brotherhood three-cylinder and then the Willans central valve. The Willans engine was admirably adapted for the direct drive of what were then called low-speed dynamos, and all records were broken by a steam economy that seemed unsurpassable. The design and workmanship seemed to leave nothing to be desired. But when the 1,000 horse-power size had been built difficulties began to appear, and it seemed at one time that the gas engine would lead the way in fuel consumption. But cyclic variations gave trouble in paralleling, and 1,000 horse-power per cylinder could not be exceeded. Electrical engineers had done much to help the development of the steam engine, and by their electrical measurements they had enabled losses to be examined and reduced and thus enabled efficiencies to be realized and measured with an ease and accuracy undreamed of before. All this vanished with the advent of the Parsons turbine, which has revolutionized dynamo design. But the turbine outgrew electrical machinery and the huge sizes were employed afloat. Now electrical engineers are catching up again with large turbo-generators, and down among the hundreds of horse-power Diesels are claiming to break records in fuel consumption, if they break nothing else.

And so the game goes on, and as in prime movers, so in almost every other branch of engineering, there is no finality and every step should be one in efficiency.

Having watched these developments, and having welcomed the successes and forgotten to lament those which were relegated to the museum, unless when I have taken a school-boy friend to see them there, one sometimes wonders if it is worth while to remember what once seemed so important, and if not worth, remembering, what was the good of it all? Well, each thing records a step to one side or a step onwards; we see, or we think we see, by now, which is the step onwards.

In engineering and in physical science we must continually realize that both practice and modes of thought are undergoing incessant change. An old Greek philosopher taught that the course of Nature is a universal never-ending never-resting process, that rest and stability are the law, not of life but of death; all things are moving, and no man can ever set foot twice in the same river.

With all the enthusiasm with which engineers welcomed these advances they knew that further improvements would surely be made and that types would change and practice alter. But we who have studied physical science, in a few of its branches, felt that the advances which would surely be made would be as it were steps hewn in the rock of the unknown towering in front of us, and that the steps which we have passed would remain for ever, even if short cuts might be found to the point which we had reached. I was taught in Chemistry that there were 64 simple elements which could not be resolved. It was possible that a few more might be discovered, but the chief difficulty was their rareness. I will not give you a list of those which must be added to the 64, but will only observe that I have lived to hear of balloons filled with helium and to see lamps filled with argon.

As for Physics, it is no longer that set of six subjects, mechanics, heat, light, sound, electricity and magnetism, with all their "laws" set out, with a formula to fit each. So bewildering has been the advance during the present century, that barriers between these subjects have disappeared, and so novel have been the hypotheses, that the late Lord Rayleigh said that he sometimes failed to understand the terms used in subjects which he had made his own.

For one first-rate instructive experiment we have a dozen underdone indigestible hypotheses. Are the foundations of physical science tottering? Shall we flutter off into a golden mist of transcendental speculation and hope to alight on some wisp of vapour that drifts past the rocks on which we have been standing, trusting that we shall not be let down to wallow in the bog of metaphysics?

From where we stand we can look back over 25 centuries of scientific history, and if you will allow me about half a minute per century I will run through the names of the old thinkers and touch on some samples of their thoughts.

In the dim distance of 600 B.C. or thereabouts, Thales taught that water is the first principle of everything. He may not have been right, but he tried to substitute a simple principle or hypothesis for the confused fancies of the poets. Aristotle, about 300 years later, suggested that Thales was not so much thinking of the boundless ocean as of the presence of moisture in all living things. Half a dozen propositions in geometry which he studied in Egypt are attributed to him. He measured the height of a pyramid by comparing its shadow with the shadow of a stick. He taught that the earth is spherical, he explained eclipses and predicted the eclipse of 28th May, 558 B.C. When he said that all things are full of gods he probably was

protesting against the arbitrary way in which the classical gods were supposed to interfere with, to favour, or to injure certain persons or places. His most famous sentence was a short one:—"Know thyself."

Axanimander thought that beyond water there was an infinite storehouse of materials from which the waste of the universe could be made good, and that the first principle is older than water and is eternal motion. This principle has been revived again and again in the history of physical science, and has been expressed in the statement that all energy is ultimately kinetic. His idea that stars are breathing holes like the holes of a flute is a childish and pretty one, If it is true that he held that the earth is a cylinder, the length of which is half its breadth, and that we live on one of the flat faces, he falls a little in our estimation.

Axinimes did not agree with the water theory, but taught that air is the one principle of everything, for it is a substance, but it is the closest approximation to a thing which has no substance. He supposed it to extend as far as thought can reach, which for those days was a fairly safe limit. We have only fragments of the writings of these men as quoted by later authors.

Pythagoras in the fifth and sixth century threw over water and air, as gross things, and declared that numbers were the absolute principle of existence. This seems to have been a dim anticipation of what we call laws of science with their formulæ, and Pythagoras would have admired the ideal of the modern mathematician, a book full of mathematical expressions with no words at all. None of these old philosophers made experiments, and few of them observed facts. They tried to distinguish between realities of Nature and illusions of sense, and to lay down general principles.

Parmenides thought that if the universe is full of matter, no motion would be possible; and Empedokles found this to be a difficulty The distinction between space and matter had not been thought of. Lucretius some 400 years later discussed the problem of a fish floating in water. The fish proposes to go ahead. The water cannot give way in front until it has been pushed. But how can the fish move to make the push until the water has given way?

Empedokles was one of the first of these thinkers who can be accepted as a teacher of physical science. He held that there are four elements, fire, water, earth and air, but he got into some confusion between air or vapour and the sky, and no wonder.

Heraklitus, to whose teaching on the continual change in Nature I have already referred, suggested that all things take place by strife, and like Empedokles he had some idea of chemical affinity and dissociation; "that which tends to unite, and that which tends to separate," or in the poetical language of those days, the harmonious and the discordant.

Anaxagoras was born about 500 B.C. Athenians could buy his work on Nature at an orchestral bookstall for the moderate price of one drachma. He developed an atomic theory, teaching that bodies are formed out of indestructible elements inconceivably minute. Considering that all this was sheer thought, we are tempted to suspect that when a good shot was made it was a mere fluke. But what do you think of this as a description of an electron written about 2,370 years ago? "So these things rotate and are separated by force and swiftness. And the swiftness produces force: and their swiftness is in no way like the swiftness of the things existing among men, but it is certainly many times as swift. . . . Rotation itself caused the separation."* Shall we call it intuition instead of a fluke?

Demokritus, born about 460 B.C., had some strange theories of light and vision which I quoted in an Address to The Illuminating Engineering Society two years ago. Zeno at about the same date is famous for two problems involving time and space. He was no engineer; he was not even concerned with physical science or mathematics. He was the first writer on logic, and propounded puzzles to show into what absurdities the mode of thought of his contemporaries would lead. Imagine an arrow flying though the air. At one moment it is in one place, and in the next moment it is in another. It cannot be in two places at the same time. But at the first moment if it is in only one place, it must be stationary. If it is stationary it will fall to the ground.

Achilles and the tortoise is still better known. Let Achilles run 20 times as fast as the tortoise, and suppose that the tortoise has 20 paces start. When Achilles has run 20 paces the tortoise will have run one pace, when Achilles has run that pace the tortoise will have run one-twentieth of a pace, and so on for ever. The fallacy is that a series such as $1+\frac{1}{2}+\frac{1}{4}+\frac{1}{8}$ continued to infinity is an infinitely large quantity. It is nothing of the sort; it only amounts to 2. This seems to be plain enough, but the tortoise has been trotted out and the arrow set flying again quite recently by the French philosopher Bergson, but whether he is laughing at his contemporaries as Zeno did is not clear.

After this, physical science met with a remarkable check. Socrates probably attended the school of Anaxagoras and must have had some knowledge of mathematics and such physical science as existed, but we have to rely mainly on Plato's account of him. Socrates thought that a knowledge of physics was unattainable, and would be worthless if attained, and he regarded the causes of physical phenomena as placed beyond the reach of human reason, and reserved by the gods for their own uses.

Now Plato was the first humanist, and set the fashion so faithfully followed by most classical schoolmasters and the many literary men trained by them, to hamper, disparage, and stop the development of natural science. It may be true that he wrote over his school, "Let none ignorant of geometry enter my door," and so long as civilization remains, his philosophy and rules of life and conduct will be studied. He was a realist, believing in the reality (whatever that may mean) of ideas (whatever they may mean), but he was confessedly averse to physical studies.

"The Athenians" for all their art and poetry "had no genius for natural science, none of them were ever distinguished as savants . . . it was a miserable trifling and waste of time quite unworthy of receiving any attention from orators, soldiers, or statesmen." They

* "The First Philosophers of Greece," Fairbanks.

had some respect for philosophy, but philosophy is not knowledge, it is the method of search for it.

Plato was closely followed by Aristotle, who lived in the 4th century B.C. A. W. Benn, from whose "Greek Philosophers" I have quoted freely, writes:— "He (Aristotle) has written about the general laws of matter and motion, astronomy, chemistry, meteorology, and physiology, with the result that he has made more blunders on these subjects than any human being ever made before or after him. . . . But his scientific treatises are, for their time, masterpieces of method."

The failure of Plato and Aristotle to advance natural science was due to their defective observation of Nature and their habit of regarding ideas and words as results. "With their prodigious intellects they went much further astray than their predecessors in the study of Nature." "Aristotle, while definitely arresting the progress of research, could still complete the method and create the language through which the results of new research have been established, recognized and communicated ever since." Bacon in his "Novum Organum" has some very hard words against Aristotle, but there have been one or two attempts of late to whitewash him.

Epicurus seems to have had a contempt for physics and the study of Nature. Then, in the 3rd century B.C. came our old friends Euclid and Archimedes, about whom I need tell you nothing, and a few pure mathematicians, and that was the end of Greek scientific work.

After an interval of about a hundred years Lucretius was born, and wrote in Latin his wonderful poem, developing the atomic theory of Anaxagoras and the theories of light and vision of Demokritus. He died about 50 B.C. Pliny is the only other Latin writer that need be mentioned.

Then there was the great gap of the middle or dark ages when science lay dead for 1,200 years. Until the 13th century Aristotle was forgotten and unknown in western Europe; it was studied in the original Greek in Constantinople. The mathematical school at Alexandria was suppressed in the 5th century. Science drifted East to Persia, and only two names are well known; Alhazen in the 11th century, and Omar Khayyám in the 12th century were mathematicians. Astrologers and alchemists practised their doubtful arts.

Then came Albertus Magnus and Roger Bacon the inventor of gunpowder, and at about this date the writings of Aristotle in Arabic were introduced into Spain by the Moors. This study was patronized by Thomas Acquinas. We can trace oriental influence in the name algebra and many other scientific terms. In about the year 1300 Arabic numerals were introduced into Italy. The use of the cypher or zero made arithmetic possible. The Romans with their hopeless notation had to use counters (calculi) for the most simple calculations.

Meanwhile, mechanical science had developed, for the splendid architecture of the Gothic type flourished in the 13th century. In 1450 Leonardo da Vinci was born and was, at heart, as great an engineer as he was a painter. Unfortunately no translation of his scientific and engineering writings has been published, but I understand that one is in preparation. He wrote in Italian, backwards, so that you must use a looking-glass to read it. You can see some of his illustrated notebooks any day in the British Museum. Michel Angelo was an architect and something of an engineer, and with Gilbert born in 1540, followed soon by Galileo and Francis Bacon, physical science leaped into a new existence and steadily developed until the present day. The secret of the renaissance of physical science was experiment and observation. Engineering, as we know it, dates from the beginning of the 18th century, and you will do your share in carrying it on. Youth looks eagerly to the future, middle age stares at the confusion of the present, old age turns thoughtfully and confidently to the past.

While some restless minds are ever seeking change, others have natures which instinctively oppose it. They show mental inertia. Obstinate clinging to an understood type is a characteristic of an old-fashioned engineer. Such men are generally slow thinkers but know their job thoroughly. They approach their work with admirable confidence, knowing that they so know it. Splendid work has been done by such old-fashioned men. The old-fashioned engineer is an obstacle to progress because he would rather do a job well in the way that he understands, than try some newfangled idea in which he has but little confidence. It is for some one else to try the new method, to prove it will work, and then to convince the other man. There is room in the world for both types, and it is well that they should be separate, for there is a danger in a kind of association of the two. When confidence, obstinacy, push and hurry are combined, the result is that dangerous thing cocksureness. Confidence is a good thing and necessary to success, but it should be qualified by a sense of proportion. The world would be intolerable if it were filled with pioneers and hustlers, and engineering would not prosper if every man were an inventor. Mental inertia is not a bad thing if it is combined with an elastic imagination.

The speed of light and sound, you will remember, depends on the square root of the quotient of the elasticity of the medium divided by its density. Air seemed to be an excellent medium for the transmission of sound until it was discovered that it travels nearly $4\frac{1}{2}$ times as fast in water and 15 times as fast in steel.

I have said something about mental inertia which like mechanical inertia is associated with mass: let us turn for a moment to mental elasticity. Engineers measure elasticity by the resistance offered by a body to forces tending to change its shape. The elasticity of steel is high and of indiarubber is low. The popular idea is just the reverse. The layman thinks more of the deformation than of the recovery of shape. The powerful drawbar spring of a locomotive and the tiny hair-spring of a miniature watch both obey Hooke's law, though the forces differ by millions, and not only is a good quality of steel needed, but it must be prepared by proper treatment. When we are up against a great thing, when at a time of crisis our powers are exerted to the utmost, and we are subjected to stress of circumstances approaching the limit of endurance, both mind and body are strained and energy is

stored up. If this is released at the right rate and properly directed, it may do great things. If the stress passes our elastic limit or yield point we may suffer what engineers call permanent set, and if the stress persists, after that comes failure. A poor spirit may have to yield to the forces because it is too soft, or if obstinate, it may suddenly crack and collapse. We should so know ourselves that we may judge our elastic modulus, and see that we have a factor of safety that will stand up to the job that we undertake.

On the other hand we have analogies of the delicate hair-spring, easily bent it is true, but of the finest steel. When our human feelings are acted upon by forces so small that they are scarcely felt, and if we react to these and respond as we ought, we exercise that quality to which the President of this Institution referred in his Address * last week; the quality of sympathy, which is so essential in dealing with our fellow-men. Think it over—I will not preach a sermon on it—the analogy between a spring and sympathy.

I will not closely examine the difference between weak elasticity and flabbiness; the distinction is sometimes difficult. Notable examples are to be found among politicians. There is a point at which elasticity disappears. Warm a jelly and it runs into a sticky mess, and when cool it will assume an entirely different shape. You know the sort of man I mean.

Then again, another class pretend to have no opinions of their own. In their youth they take pride in making speeches in debating societies on the side opposed to their own convictions. In after life they become distinguished barristers or journalists or some other kind of word-monger.

The excuse for men of such temperament is that they are dealing with opinions, and not like those engaged in engineering and physical science with things. We engineers admire exactness of thought, and accuracy of workmanship. In making an experiment an engineer or scientific man must of necessity be honest. He is out to obtain a result, and to cheat would merely be to cheat himself. When he describes it he tries to use language which shall convey the truth. To be vague would be unscientific. It is only in dealing with men that we are tempted to use the methods of diplomacy. When we have a difficulty in getting a galvanometer to work we do not think of trying a little flattery or toadyism, telling it what a fine galvanometer it is, and how proud the college is of it. When a motor is obstinate and will not start, since you know how it is made you can test for continuity or leakage and spot the trouble, give the bearings a drop of oil, and off it goes. But in after life you may have to deal with an obstinate Town Clerk. Do you know how Town Clerks are made? Do you know their weak points? We must not press the analogy, but the cunning and subtlely required to make him go is very different from the direct methods which you apply to the motor. Those other methods are not taught in colleges.

In dealing with a machine you *must* deal directly and honestly, and the machine will deal directly with you. It may be unwilling to let you find out what is the matter with it, but it will not prevaricate, exaggerate or tell you a lie. It may knock you down, but it will not hit you when you are down, and try to injure your reputation. It is only in dealing with men that we have to reckon with meanness, jealousy, jobbery, evasion, sharp-practice and, in short, what are known as political methods.

Of course, business is business, and most of you will find that the sordid side will spoil a good deal of your enjoyment in engineering. It is possible, in this country, to be an honest business man, and an honest engineer, yes, and an honest statesman.

I have told you that there are different ways of measuring success. You who have your hearts in your work will find that opposition which comes from the forces of Nature can be met directly by your engineering and scientific knowledge. If you have to get some hundreds of tons of plant on its foundations, your tackle can be arranged and everything should go according to plan. When it comes to lining up and adjustments, you will work to a thousandth of an inch, and you may be confident that sound workmanship will ensure good running. All this is a matter of training and conscientious work. In craftsmanship of the highest class, such as in the final adjustment of a gauge, to two or three 10,000ths of an inch, there is a thrill or feeling of exaltation as the last few strokes are made. The feeling is no doubt deadened by long use, but the satisfaction of a good job well done is worth having.

When a generating set runs its trials, keeps cool, shows a good fuel consumption, and high efficiency, regulation, paralleling, and all that it is expected to do, or when a gauge is tried by a competent inspector and accepted, there is no question so far as to success. As long as we are working with inanimate things our powers are in our own hands. But in dealing with human forces the opposition that meets us is so complex that we often do not know if or when we have succeeded.

Almost all important engineering undertakings are carried out nominally under the direction of a town council or other local authority, or of a board of directors of a company. An engineer is generally the servant of one of these bodies, and the success of his work, and therefore his own personal success, depends greatly on his relations with his employers. No lectures, no experiments, no textbooks, no branch of science that was ever discovered can help. Nothing but observation and experience and tact is of any use, for when an engineering problem is submitted to a committee or to a board of directors or to a government department, the attempt to carry it through is made against very different forces from those which we call the forces of Nature. You will not come up against these difficulties in the early stages of your career, but you should not let opportunities pass for learning something of such work.

On a committee or board there is generally one man or at the most two who can and who ought to do any particular job. The others, from a sense of duty, feel that they should help or share the responsibility, and what they generally do is to smother the matter with more or less irrelevant suggestions. If there

* *Journal I.E.E.*, 1920, vol. 58, p. 1.

are two or three different ways of carrying out the work, the right thing to do is to decide the way, and then to do it. But the usual course is to make a compromise which ends in a muddle, unless the men who really understand carry their way. As often as not, somebody's feelings are wounded. This is supposing that all is fair and above-board and all want to carry the work through. But when there are factions and private ends, even of so innocent a description as the gratification of vanity, operations become very complex.

The culmination of such control is that of Parliament. The industry of electrical engineering has been the plaything of the political platitudinarian, and the foible of the fussy official. The lamentable feature of such work is that after almost every good intention has been ruined by compromise and when it is nominally done, that is, when the Bill is passed or a Regulation made, the work is really only just begun. Those who have been responsible, gaily divest themselves of any care about the matter and go and interfere with something else. Perhaps it is as well, for when they have done their worst (with of course the best possible intentions) it remains for somebody who understands to make the thing work. The amount of time that skilled engineers have to spend in the Committee rooms of Parliament, and the kind of work which they are expected to do there, either in initiating obstruction or in fighting against it, is lamentable. I believe that nothing corresponding to it is found in any other country. But until things are altered, engineers will have to undertake such work. I hope that most of you will escape the necessity of helping in it.

Few of you will lead the kind of life you plan. I have said already, opportunities will offer, and you will take them, if you think that you can do the work. You cannot always tell that in advance, but you can always do your best.

We generally hear about the square peg in the round hole. That is a very different thing from a round peg in a square hole. The square peg only fills $2/\pi$ or 0·6366 of the space, and if it is jammed in, it digs four sharp edges into the sides of the hole, or if those sides are unyielding, and the peg is of weaker material, its edges will be blunted. The round peg is much superior. It occupies $\pi/4$ or 0·7854 of the space, that is, 23·5 per cent better. If driven in, it will only make mild bulges in the flat walls or slight flats on itself.

Government service, civil or otherwise, used to be a mass of adamant pierced with hundreds of thousands of holes. The large majority of pegs which aspired to occupy these holes used to pass through the examination machine which sized them, operating on them while still in the young soft stage, with the gratifying result of a fairly good fit. The fit could be improved by gentle pressure. Shortly before the War several thousand pegs of a nondescript kind were tossed into the holes formed by a kind of political ferment, and during the War government service became a huge honeycomb, the honey amounting to 20 shillings or 30 shillings a week, and the pegs hardly made any sort of a pretence to fit. Thousands of these have been shaken out.

I think you will be happier as rolling stones than as pegs, until you are old enough to calliper your own diameters with confidence and to gauge holes that are offered, with accuracy; and may they be round ones!

Let me finish with a quotation from a speech made at a banquet of the delegates of the International Electrotechnical Commission a month ago by the Father of British electrical engineers, Colonel Crompton:

"I am an old man, and I am a happy old man, and I feel that there is only one thing for us old people to look back to, and that is the feeling that we have been the means of doing some service to others, so that when we pass away our work will be thought of."

PROCEEDINGS OF THE INSTITUTION.

639TH ORDINARY MEETING, 27 NOVEMBER, 1919.

(Held at the Institution of Civil Engineers.)

Mr. ROGER T. SMITH, President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting of the 13th November, 1919, were taken as read, and were confirmed and signed.

Messrs. P. B. Frost and N. W. MacLachlan were appointed scrutineers of the ballot for the election and transfer of members, and, at the end of the meeting, the result of the ballot was declared as follows :—

ELECTIONS.

Members.

Hoare, Arthur Richard.
Jones, David George.
Pletts, John St. Vincent
Robertson, Frederick William, Bt.-Lieut.-Col., O.B.E., R.E.
Slee, John Ambrose, Capt., C.B.E., R.N.

Associate Members.

Abraham, Albert William.
Ainsworth, Stuart.
Allbut, Guy.
Ardis, Robert.
Ariger, John.
Arnold, Kenneth Noss.
Aston, Clifford John, Major, R.E.
Atkinson, Edgar.
Baines, Thomas Humphreys.
Barrett, Albert Harry.
Bedbrook, Lewis Ambrose B.
Bell, Norman Macleod.
Bevis, Henry James.
Blake, Ernest.
Bond, Ernest Harry.
Boraston, Charles Albert, B.Eng.
Bowman, Hugh Marshall.
Brown, Robert Cranmer.
Browne, William Frederick.
Bullen, Arthur Tom.
Bygrave, Leonard Charles.
Calvert, Ernest Edwin.
Carr, John Liddell, B.Sc.
Carter, Harry, B.Sc.
Cartmell, Cuthbert.
Catt, James Edward.
Causer, Donald Stuart.
Cleaver, Richard Lovell, B.Sc. (Eng.).
Clegg, George Dudley.
Cox, Arthur William.
Crum, Thomas Good, B.Sc. (Eng.).
Davies, Garnons Hugh.
Demaine, Charles Snowden.
Dickin, Horace Croxall.
Evans, Charles Leopold.
Evans, Sydney Lawrence.
Faulkner, Joseph William, B.Sc. (Tech.).
Freeman, Ernest Richard.
Fuller, William Henry.
Gann, Walter Thomas.
Girvan, William John McC.
Glover, Edward Otho.
Golland, Edgar.
Gosling, Arthur Starr, 2nd Lieut., R.E. (T.).
Grundy, Edmund Eric L.
Henderson, Quintin McGill.
Herring, Frederick William M.
Hitchcock, Edward.
Hughes, Cyril Thomas.
Illingworth, Robert.
Inman, Oliver.
Isaacs, Reginald George, B.Sc.
James, Charles.
Johnston, John Stanley.
Jones, Charles Harold.
Jowers, Harold Hill.
Keen, Ronald, B.Eng.
Ketèlbey, Frederick George.
King, Edgar Wilfred.
Kirkby, Ernest Octavus.
Leason, Harry.
Lee, John Andrew.
Lilleker, James Robinson.
Lingard, Arthur.
Lingard, Ernest.
Lockhart-Jervis, Beresford Clayton, Major, D.S.O., R.E.
Low, Peter Dunstan, Major, O.B.E.
Lunn, Philip.
MacArthur, Duncan.
Macfarlane, Charles Frederick.
McKinney, John Alexander.
Maddock, William Trevor.
Martin, Valentine, B.Sc.
Matthews, Thomas Herbert.
Midworth, Cyril.
Miller, Leonard.
Mills, Charles Joseph.
Misso, George Elibank.
Mitchell, James.
Moffat, John.
Mold, Leonard Ernest.
Monson, John Percival.
Montgomery, William Russell.
Mullowney, Joseph.
Munday, Henry Ernest.
Naismith, James Ebeneza.
Nicholls, Francis Abednego.
Nicholson, James Kelty A.
Paranjape, Vishnu Kashinath.
Parker, Harry.
Parker, John Neville.
Parker, Samuel Rutherford.
Payne, Benjamin William.
Pellow, Ernest.
Phillips, William Arthur, Lieut., R.E. (T.).
Porter, Ernest Eversley R.
Read, Frank William.
Reed, Arthur Price, Major, R.A.F.
Reeves, Stewart Kenneth.
Rendell-Baker, Frank Nelder.
Repton, Leonard.
Richards, Samuel Hope.
Rowbotham, Sydney Lloyd
Ryder, Percy George.
Sale, Harold George.
Scott, Wallace John D.
Seddon, John Massey.
Severn, Albert Ernest.
Smart, Edwin Victor.
Smyth, Charles Carew.
Snook, Edward Henry.
Sturman, Sydney William A.
Sykes Arthur Clifton, Capt., O.B.E., D.S.O., R.E.
Thomas, Arthur Glyn.
Thomas, George Nevil.
Tippin, Leopold Alger.
Todd, Thomas David.
Tucker, Charles William A.
Twinch, Walter.
Urmston, James.
Vigor, Frederick Kennard.
Wallbridge, Charles Seaforth.
Walter, William George.
Ward, John Henry.
Ward, Richard Gibbs.
Warren, William Austin.
Weir, William.
Wilkinson, Arthur R.
Willcocks, John Samuel P.
Willmore, Thomas.
Wilson, George Saunders.
Wilson, William Wallace.
Wittey, Percy Oscar.
Wooler, Lionel Sykes.
Wright, Harold George.
Wrighton, John Charles.

Graduates.

Acock, Charles Edward.
Adams, Ernest Hirons.
Andersen, Reginald Charles.
Andrew, William Henry.
Astley, Harold.
Berriman, Robert Harrold, B.Sc.
Bhadury, Sushil Kumar.
Bindler, Michael, B.Sc. (Eng.)
Briggs, Bernard George.
Brown, Edward.
Burbridge, John, Junr.
Burt, George William.
Caine, Allen Flinders.
Cameron, Donald Lochiel.
Campbell, Farquhar Clark.
Carter, Stanley.
Chapman, Gerald Sidney.
Coldwell, David Kidd.

Graduates—continued.

Court, Arnold Frederick.
Davis, Harold Norman.
Dennis, William Edwin.
Diaz, Enrique, B.Sc.
Duncan, Hugo James, M.C.
Ford, Joseph Manning.
Fox, Herbert Christopher.
Guthrie, Alec.
Habberjam, James.
Hatley, Alfred John, B.A.
Henderson, John.
Holmes, Hubert Jack, M.B.E., M.C.
Latorre, Antonio.
McAteer, Desmond O'Boyce.
Mackintosh, Illtyd.
Monk, Sidney Gordon, B.Sc.
Moore, Eric John T.
Mylchreest, Henry William.
Orme, Alexander.
Pantcheff, Sophocles Xenophon.
Roddis, Charles Henry.
Stinson, Frank.
Waddington, Rupert Ronald.
West, Stanley Birkett.
White, Herbert John F.
Williams, Charles Stewart, M.C.

Students.

Armitage, Ronald.
Badham, Leonard Hulford L.
Ball, Walter Reginald.
Barnes, William Charles.
Barrand, Percy Christian.
Beaumont, Leonard.
Bennett, Horace William J.
Best, Frank Powell.
Bibby, William.
Bonny, Arthur George A.
Brock, David Henry.
Brock, Harry.
Bronsdon, Eric Norman.
Brooks, Samuel Arthur, Lieut., R.N.
Buckley, Horace.
Buckman, Henry Leonard.
Buttress, John Harold.
Carlisle, Sydney.
Carpenter, George Murray.
Charlton, Howard Cunningham.
Colley, Robert.
Colquhoun, James, B.Sc.
Cooper, Arthur.
Cooper, Francis Howard.
Corner, Arthur Charles.
Dally, David Charles.
Davies, David Percival.
Davies, William Thomas.
Davis, Percival William.
Dobeson, Richard Gray.
Dransfield, Frank.
Dransfield, Stanley John.
Duckworth, Arthur William S.
Edmonds, Peter Leonard.
Ely, Raymond Edward V.
Etherington, Herbert Edmund.
Fisher, John Jacob.
Ford, Stuart Leslie.
Gibbs, William John.
Gordon, Harry Harold.
Grant, Lewis Colin.
Green, Wilfred Buller.
Greenwood, Walter.
Haigh, Harry.
Hambridge, Cecil James.
Hart, Morris Daniel.
Henderson, Frederick Ewart.
Hickleton, Charles John.
Hill, Kenneth Arthur.
Hine, Frank Walter.
Holmes, William Temple.
Hudson, William Edward.
Illingworth, Joseph Priestley.
Johnson, Francis Hannam,
Kernick, Richard Conrad.
Kilner, William Norman.
Lancaster, Jack Kelvin.
McCarthy, Harold Cuthbert.
Maxfield, George Willie.
Morley, Robert.
Nye, Alfred George.
Oldham, Charles Albert.
Parr, Geoffrey.
Penstone, Walter St. George.
Pocock, Geoffrey Crawford.
Powell, Thomas Arthur.
Purvis, Leslie.
Redfearn, Charles Herbert.
Roberts, William Henry.
Robinson, George.
Rock, Dennis Ivan B.
Rolleston, Owen Molony.
Sclar, David.
Skinner, Alexander Finlayson.
Spencer, Albert Victor.
Stacey, Ernest.
Stewart, James Campbe.
Storey, Stanley Percival.

Students—continued.

Stubbington, Reginald William.
Tinsley, Horace.
Tourover, Raphaël.
Turnbull, Edward James.
Tydd, Arthur Gordon.
Unwin, Dudley James.
Warner, Irving.
Wauchope, George Andrew.
Warren, Alfred Charles.
Waters, Herbert Reginald.
White, Sidney Robert.
Windle, Allan Austin.
Woodiwiss, William.
Wynne, Richard.

Associates.

Andrews, William Archibald, B.Sc.
Boyd, William Robert E.
Chapman, Arthur Edward.
Cohen, Jacob Waley.
Eastick, John Clare N.
Hanby, Wilfred.
Hider, George Ernest.
Ingram, John, B.Sc.
Lloyd, Daniel William, B.Sc.
Mann, William, B.Sc.
Nightingale, Ernest, M.Sc.
Thompson, Charles James.

TRANSFERS.

Associate Member to Member.

Davies, Arthur Everitt V.
Ghosh, Surendra Nath.
Martin, Richard Harington.
Peake, Cyril Vivian.
Pope, William Godfrey T., Major, M.C., R.E.
Tanham, Richard.
Williams, William John.

Graduate to Associate Member.

Booth, Henry Isaac.
Borland, James Holliday.
Bowers, Edwin Guthrie, M.C.
Chandler, Charles Kingsley, M.B.E.
Chatterji, Professor Bhim Chandra, B.A., B.Sc., B.L.
Hainsworth, Albert John.
Higham, Ralph Gilson.
Leivesley, Herbert Gladstone.
Preston, Ernest Bloxsidge.
Willcock, Arthur.

Student to Associate Member.

Aylmer, John, M.C.
Boulding, Reginald Sidney H., B.Sc.
Hellaby, Joseph Arthur B.
Herring, Edgar John C.
Morrell, Percy.
Protheroe, Roderick Norman L., M.C.
Rodwell, James Theodore, Major, O.B.E., R.A.F.

Associate to Associate Member.

Hedberg, Trevor.

Student to Graduate.

de Boissière, Eugène Ernest M.
Exley, Walter.
Hogarth, James Edward.
Padgett, Albert Stanley.
Wong, Tai Cho.

A paper by Messrs. C. C. Paterson, O.B.E., Member; J. W. T. Walsh, M.A., M.Sc., Associate Member; A. K. Taylor, Member; and W. Barnett, entitled "Carbon Arcs for Searchlights" (see page 83), was read and discussed, and the meeting adjourned at 7.45 p.m.

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FAILURES OF TURBO-GENERATORS AND SUGGESTIONS FOR IMPROVEMENTS.

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Until about the year 1903 practically all large generating units were of the low-speed marine-type engine with low-speed generators directly mounted upon the shafts. These engines were excellent examples of design which had been evolved during many years' experience with mill and marine engine practice; and with sound workmanship common to all the best class of British shops, the plant was of great reliability and could with confidence be expected to have a physical life of nearly the human span of years. The low-speed generators coupled to those engines were equally massive and substantially designed, and gave practically no more trouble than did the engine flywheels themselves. The economic life of such plant, however, was immediately shortened by the rapid progress of steam turbo-generators, and nearly all the fine examples of engine generators have now been discarded and scrapped.

The relative steam consumptions, taken from running records, are of the following character:—

Type of Plant	Year	Size	Speed	Steam		Vacuum	Steam per kw.-hour
				Pressure	Temperature		
		kw.	r.p.m.	lb.	°F.	in.	lb.
Compound engine	1904	4,000	95	200	550	26	18
Impulse turbine	1909	5,000	750	200	550	28·5	15
,, ,, ...	1912	8,000	1,500	200	550	28·5	13
,, ,, ...	1918	20,000	1,500	200	600	29	11

Whilst the steam economy of turbo-generators compared with engine generators is most marked, unfortunately the same favourable comparison does not hold for reliability and physical life.

The reason is fairly obvious in so far that the necessary time has not been available in which to gain experience and evolve established designs; the size of machines and of the systems in which they are established is constantly increasing, and each increase opens up new difficulties for solution and consolidation.

The difficulties of design and manufacture have been so ably set out by both British and American designers during the last few years that it might appear that a paper from an operating engineer could not fulfil any useful purpose, particularly if he is not an expert constructor. On the other hand the operating engineer usually occupies a position of greater freedom to criticize, to represent the difficulties experienced, and, within the limitations of his knowledge, to indicate

certain new ideas which appear to him helpful in overcoming such defects.

As a rule, serious failures with turbo-generators only develop when machines are of large size and form units in a system of some magnitude. Under these conditions any fault on a single unit may then be fed from the collective energy from several machines until the protecting relays of the switchgear have operated. As a result the failure of a turbo-generator is usually more or less complete, and if, as generally happens, the machine is set on fire, it may be several hours before it is cool enough for examination. By that time the charred remains are in such a condition that evidence of the cause of breakdown has usually been entirely destroyed, and it becomes a slow and painful business to diagnose with any certainty the source of weakness, and with confidence to prescribe a remedy.

After several years of experience in many stations and with different designs of machines, the more usual types of failures have been determined and may be roughly classified under :—

(1) Mechanical weakness,
(2) Electrical weakness,
(3) Heating and fire risk,
(4) Ventilation difficulties.

The various defects are generally very closely correlated, as will be discussed later in the paper.

Mechanical Weaknesses.

The efficiency of the steam turbine increases materially with its speed, and modern generators are now run at speeds which would not have been considered practical six years ago. The centrifugal stresses in the rotor teeth, upon the rotor coils and their insulation are serious in amount, particularly so with speeds of 3,000 r.p.m., the centrifugal forces increasing with the square of the speed.

To limit these stresses and retain the maximum speed of rotation, the diameter of the rotor is reduced to the smallest practical dimension, the increase in size for increasing output being more in length than in diameter. As a result, the running speed of the generator is generally above its first "critical" speed, except in the case of the double generators of the Ljungström combination, and therefore each time the plant is started and stopped the rotor must pass through the first critical speed with its attendant risks. The cylindrical pattern of rotor with radial slots originally adopted by Messrs. Brown, Boveri & Co. has now become universal, and generally the rotor and its shaft are turned out of a single forging.

One serious result of the high speeds of rotation is the difficulty of effectively holding the rotor coils against centrifugal forces. The portion of the coils within the winding slots is retained in place by metal wedges driven into dovetailed recesses machined out of the top of the rotor teeth. The portion of the windings forming loops at each end of the rotor cannot be held in this manner. Originally they were secured in place by steel wire bands wound tightly upon the completed coils.

An advantage of using drawn steel is that the highest quality of material can be obtained, which from the very nature of its manufacture has been thoroughly tested on the draw bench, and moreover the material is reasonable in price. Such steel bands are, however, open to grave objections. As the windings are usually cooled by air ventilation underneath them, they are arranged more or less in an open form and not clamped to an internal hub. In consequence there is a tendency for the coils to set in radially, thus slackening the steel bands upon them and throwing the rotor out of mechanical balance.

When a short-circuit occurs at the ends of either the rotor or the stator, the bands are usually fused and the steel wires rapidly unwind. Again the ends of the wire banding may become unanchored.

Whenever a wire band fails, the result is invariably the wreckage of the rotor and stator windings, with more or less serious destruction of the ends of the stator core.

Consequent upon these troubles, solid rings of high tensile steel are now used instead. These rings are turned out of substantial forgings in which internally hidden flaws may exist, and, from the standpoint of reliable mechanical strength alone, they have not the advantage of drawn wire bands. Moreover, alloys like nickel and chrome steel are comparatively new, and the effect on them of prolonged heat and continued stress has yet to be determined. If, during ageing, a slow and continuous reduction in elastic tensile strength occurs, a periodic renewal of the bands will be necessary. The failure of a band is a catastrophe to be avoided at all costs, for it generally results in serious loss of life and plant.

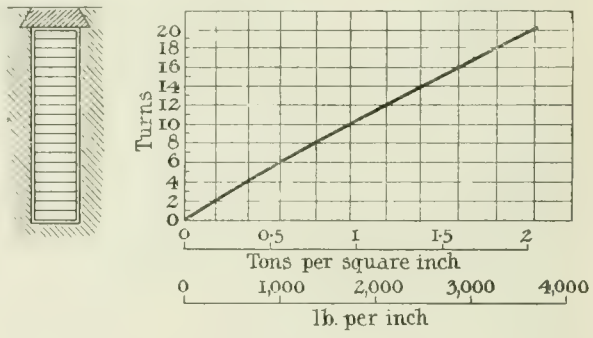


Fig. 1.—Centrifugal stresses in rotor windings.

As an extreme example, Fig. 1 illustrates the radial stresses in pounds per inch of coil length from turn to turn of such a rotor coil, the rotor being of 36 in. diameter and 3,000 r.p.m. The stress increases in a parabolic curve from the bottom of the slot. The same curve to a different scale represents the crushing force per square inch on the insulation between the turns. Assuming that the turns are absolutely flat upon each other, giving uniform pressure throughout their area, the pressures per square inch in the example taken are :—

Between the complete coil and wedge	4,600	lb. per sq. in.
Between the last two turns ..	4,340	,, ,,
Between the first two turns ..	200	,, ,,

The choice of insulation capable of withstanding such pressures is very limited, especially as prolonged heating of the insulation and the difference between the expansion of the copper and of the wedge are also involved.

The portion of the rotor winding within the rotor slots must of necessity preserve its shape under the centrifugal forces, but the unsupported portions of the coils at the end loops have no lateral support, and there is always a risk of distortion or side slip at high speeds. The problem in certain respects is similar to that of a short strut under heavy compression, the strut being severed into many sections piled upon each other.

For many years a flexible type of coupling between the rotors of the alternator and turbine was generally used. Such flexible couplings required two bearings each for the turbine and generator. The couplings were usually of a muff form with internal teeth engaging with half couplings having external teeth secured to the rotor shaft. As the size of the combination increased, mechanical difficulties were experienced owing to the imperfect line contact on the driving faces of the teeth. Further, the coupling could with difficulty be maintained in good running balance, and it was questionable whether the connection was really of a flexible character. Some 12 years ago, Continental makers began to discard flexible couplings, and that practice has now been followed here.

The internal losses of a modern generator are about 4 to 5 per cent of the rated output, and the heat resulting from these losses is almost invariably dissipated by forced air ventilation through specially constructed air vents in the rotor and stator. In the rotor these vents are provided under the slot windings and, to find room for them, the rotor must be increased in diameter, with increasing difficulties from centrifugal forces. With higher speeds, smaller diameters, and increased length of rotors, it becomes a matter of great difficulty to pass the required amount of cooling air through the rotors. Generally there is adequate room in the stator for the air ventilating-spaces at the expense of iron space. On modern machines, the volume of the stator taken up by ventilating spaces is from 15 to 25 per cent of the total volume. The stator is divided longitudinally by air ducts spaced about 2 inches apart, the passages being maintained by spacing fingers attached to the steel stampings. In addition, longitudinal air passages are provided in the cast-iron framework behind the discs and sometimes through the stampings in addition.

This method of open construction gives a mechanically weak form of stator core and, under the alternating stress, chattering of the teeth may occur with consequent breakage. The result of the vibration on the insulation of the stator bars is obviously undesirable, without the further trouble of broken teeth. A further mechanical weakness occurs at the end of the stator where the winding must have spacings for the air freely to pass between them. The windings although mechanically and almost continuously held in the winding slots can only be clamped at intervals along the end connectors.

Another mechanical defect in the stator is the method of attaching the stampings to the frame. In earlier designs of generators, each stamping had two (or more) dovetailed keys on each sector, and these keys were threaded into machined keyways cut in the cast-iron frame as shown in Fig. 2. The cheaper form of construction afterwards adopted on the Continent was to stamp the dovetailed keyways in the sectors as shown in Fig. 3, with corresponding keys let into the frame. This construction does not give so direct a connection to the frame as the former, and has been the cause of numerous failures. With faulty workmanship and inadequate proportion of the keys, the core worked slack at the keyways, with complete failure of the stator after a few months' working. In other cases the volume of iron has been insufficient. and the induction in the iron near the keys has caused serious overheating of the stampings and reconstruction

FIG. 2.—Stator sectors with external teeth.

FIG. 3.—Stator sectors with internal keyways.

of the stators became necessary. The probable cause was the formation of eddy currents in the steel keys, with the overheating of the keys and the portions of the discs near them. With certain conditions of load, this overheating became so serious as to burn off the paper insulation on the discs and to throw out a shower of sparks from the burnt paper at the air discharge. The former construction having dovetailed keyways punched out of the stampings gives a sounder machine. At the same time the later method may give a good machine provided the keyways are well punched, of adequate size, and that proper allowance is made for the active metal lost by punching the keyways out of the sectors.

Inaccurate punching of the plates is another source of trouble, entailing excessive filing of the stampings after building; and to prevent serious eddy currents across the burrs caused by the filing, the plates are more lightly packed together than is desirable and vibration takes place.

Owing to the limitation of railway facilities the

stators of large generators must be built on site under usually somewhat primitive conditions. Consequently the preparation of the stampings and their building up is not always so carefully carried out as when erection takes place in the shops.

Electrical Weaknesses.

The electrical weaknesses in turbo-alternators have generally developed since the size of the machines and the systems to which they were connected increased to over 30,000 kw. on a single set of busbars. The insulation on the stator bars is almost invariably micanite, worked on hot with a Haefley wrapping, and a thickness of 0·15 inch of insulation is usually sufficient for ordinary working pressures. Micanite insulation is admirable so long as it is not overstressed during short-circuits. If, however, the stator bars are not adequately supported, bending will occur and cracking of the micanite insulation will result, usually just inside the ends of the stator core. As a rule such a crack cannot be detected, and its very existence is unknown until a breakdown occurs, perhaps weeks or months afterwards.

With the exception of the lack of flexibility, micanite insulation on a straight bar is in every way admirable, and is much the best kind of insulation at present known. To overcome this defect a number of different types of insulation have been introduced using Empire tape and similar fabric, interleaved with mica. Insulation of this character when new is fairly flexible and will yield a limited extent without cracking. After use at the ordinary working temperature of turbo-alternators the fabric loses its flexible character and becomes as brittle as mica.

From the constructional point of view the one bar per slot of stator winding has advantages. The bars are of reasonable size, and the number of joints is less. There is the important advantage of thinner insulation and smaller temperature gradient across the insulation.

Owing to the considerable depth of the stator slots, considerable magnetic leakage takes place across them, and division of the stator bars is necessary to reduce eddy currents in them, especially if the bars are of substantial size.

Continental makers, working under patents of Messrs. Brown, Boveri & Co. and the A.E.G., construct the bar of various laminæ, which are twisted within the slot relatively to each other.* The joint between the bars and the end connectors is a matter of some difficulty; generally it is soldered, and if care and time be taken a sound joint can be made by experienced workmen. There is, however, always the difficulty that out of hundreds of joints in a machine one may be defective. During construction a defective joint may be detected by a fall of potential measurement, or by circulating a current much in excess of the maximum full-load current through the windings and feeling for hot joints. These tests are not infallible, nor are they always carried out, and unfortunately defective joints are met with. The presence of one undetected joint on a working machine is a matter of very serious anxiety. As its position is not known, it cannot be kept under observation, nor is it feasible to untape the joints and strip down the machine every time it is stopped; and even if it were, this would not be an absolute safeguard, for the same machine may run continuously for months together. In practice it usually happens that a faulty joint is only detected through the machine giving way and the solder melting, with every risk of a fire.

The greatest electrical weakness in turbo-generators constructed a few years ago was their inability to withstand the stresses set up on short-circuit. If even moderate movement of the stator bars occurs, cracking of the insulation is probable, especially if the insulation is of some age, setting up a defect which will develop sooner or later into serious trouble. If a solid conductor could be used, a very rigid bar construction is possible, and the risk of the conductor bending under short-circuit would be small. As an example, in Fig. 4 is shown a three-turn per slot winding for a 5,000 kw. machine, 6,600 volts between phases.

Fig. 4.

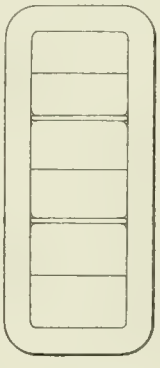


Fig. 5.

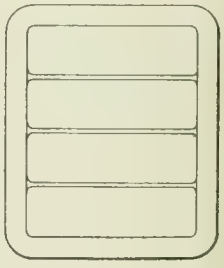


Fig. 6.

Fig. 4.—Stator winding, three-turn bar divided radially.
Fig. 5.—Stator winding, three-turn bar divided axially.
Fig. 6.—Stator winding, one-turn, four bars in parallel.

The three copper tapes are arranged lengthways in the slot, giving a stiff bar with which there was no trouble on short-circuit. In Fig. 5 is shown the winding of another machine of similar size, laminated across the slot, and of better design for reducing the eddy currents, but the bar is not so rigid. Both machines worked under similar conditions, and were connected to the same busbars, but the winding shown in Fig. 4 gave no trouble on short-circuits, whilst the winding in Fig. 5 repeatedly broke down. In later designs the lamination of conductors has been carried to much further lengths, so much so that the insulation upon the conductor really supports the bar.

On the multiple bar and crushed strand construction, difficulties occur with stator bars of considerable section. The conductors do not nest firmly together, and a tight mica wrap around them cannot be made, so that there is always a certain amount of slack between the conductors and the mica around them. An example is shown in Fig. 6 where the conductors were slack

* A similar construction is also adopted by English makers, and a number of British patents covering stator-bar lamination are enumerated in the Appendix (page 140).

within their insulation, and in less than three years the insulation was worn away at the corners and caused a breakdown to earth at a very moderate working pressure.

The latest method of constructing stator bars is a more complete development of lamination. The stator bars are divided radially into several copper tapes, each separately insulated, and each tape is connected to another tape in the several bars forming the winding pitch at the ends of the stator. At each joint the tapes are twisted relatively to each other, giving a complete change of position in each complete phase winding from the star point to the main terminal.

This construction eliminates eddy currents and gives a uniform distribution of current in every section of the stator bar. It has the additional advantage of small joints, which enable the tapes to be fusion welded together. The only large joints occur at the star points and at the main terminal connections, and these can be arranged well out of the revolving field. However, a bar laminated so completely has little stiffness or mechanical strength and requires very careful support.

The popular remedy against short-circuit stresses is the provision of high reactance within or without the machines, reducing the current on short-circuit to from 8 to 10 times full-load current. This reactance can be built into the machine itself by providing the necessary magnetic leakage, and internal reactance gives the greatest protection to a machine. External reactance gives protection from feeder or busbar troubles, but not from internal short-circuits. But whether the inductance be internal or external, the result on the regulation of the machine is the same, resulting in poor regulation.

In addition to the short-circuit stresses, there is mutual attraction between the adjacent end turns of the same phase, and repulsion between the adjacent end turns of different phases. The attractions and repulsions increase as the square of the alternating current, causing vibrating forces corresponding to twice the periodicity of the system.

In large generators the ordinary method of leading away the current of the stator is open to improvement. The winding is usually terminated in split connections, clamped together by small screws with slotted heads, a somewhat crude finish for a plant of considerable size. In all large systems it is more satisfactory to lead away each phase by a separate lead-covered cable, taking care that substantial joints are made between the cable and the stator windings, and that such joints are well clamped mechanically against all possible movement.

Heating and Fire Risk.

With the old type of low-speed generator the fire risk was not considerable, as the proportion of inflammable material was small. With a modern tubo-alternator the conditions are quite different; and owing to the high speed and compact design with small volume of active material, a very considerable portion of inflammable insulation is built into the machine. As a consequence of forced air ventilation, the generator is totally enclosed and, when working, no part of the winding is open to inspection. A fire within the machine can originate in a variety of ways, such as defective joints, a short-circuit to earth or between the stator windings, failure of insulation or the like. An arc, however started, has immediately a considerable amount of energy fed into it, until the field current is cut off and the machine isolated from the busbars by relay protection. If the machine and the system of which it forms a part is of considerable magnitude, the energy fed into a short-circuit is enormous, and in effect is nearly as dangerous as an explosion, so that the relays may or may not be capable of operating with sufficient speed to prevent serious damage to the machine.

With high-speed turbo-alternators the stators have usually two-pole windings, consequently about 50 per cent of the stator winding length is usually taken up by the connectors between the stator bars. These connectors are purposely spaced in an open manner to allow the cooling air to circulate, and the air is circulated at the speed of a tornado and is constantly renewed by the fans. The inflammable character of the winding may be augmented by oily vapour and dirt carried into the machine by the ventilating air and deposited as sticky material on the conductors.

There is comparatively little fire risk with the windings which are enclosed within the winding slots, as the cooling effect of the surrounding iron is considerable. But a fire once started at or near the end connectors is immediately swept round the openly spaced windings, and their destruction is a matter of only a few seconds. To make matters worse, the momentum of the rotors causes continual rotation for from 30 minutes to upwards of an hour after the steam has been shut off, depending on the speed and size of the machine.

If air dampers are provided in the external ventilating air ducts, it is doubtful whether they could be closed sufficiently quickly to cut off the air supply and save the machine, or if there would not be sufficient air leaking past the dampers to continue the conflagration sufficient to wreck the machine even when the dampers are closed. The first intimation of anything being wrong is usually the presence of smoke and sparks at the air discharge of the machine, and every second elapsing afterwards is of vital importance.

The same objections also apply to other devices proposed for preventing the spread of the fire by flooding the interior of the machine with nitrogen, carbon dioxide, carbon tetrachloride, etc.

Even although the insulation of the machine be not actually consumed, it is usually left in so charred and brittle a condition that a rewind becomes desirable.

Ventilation Troubles.

The amount of air required to carry away the internal heat is dependent upon the internal losses and upon the permissible temperature rise. Allowing a rise of 50 degrees F. in the cooling air, and a loss of 4 per cent in the generator, about 4 cubic feet of air per minute per kilowatt of output is sufficient, and this allows for a certain amount of the air being short-circuited within the machine. Even under the cleanest conditions the air has sufficient dust suspended to choke up the internal ventilating spaces in time, and filtration of the air becomes

necessary in some form or other. Further, even in our temperate climate it is desirable on the hottest days of summer to cool the incoming air. Dry air filters were originally introduced for removing the dust, and are still largely used on the Continent and in America. The filtering cloth is of considerable area, its renewal is troublesome and is often postponed until the pores of cloth become filled with dust, the full allowance of air not being admitted.

Air washers of the spray type have been used to a considerable extent in this country, but in several cases they have not justified the high opinion in which they were formerly held, and more or less free moisture has been introduced into the machines by their use. Except in very exceptional conditions some form of filtering the cooling air is necessary. The amount of dust caught by a dry filter from an air blast of 40,000 cubic feet of air per minute has been found per week of continuous working to be 5 lb. in the centre of London and 2 lb. at the outskirts of London.

Unless this dust be removed, it is sufficient to choke up the narrow air passages in the rotor and stator, which passages can be cleaned only with considerable difficulty, even when the rotor is removed.

The air is generally drawn into the bottom of the machine by fans attached to the ends of the rotor. In large high-speed machines the fans may be external to the machine and separately motor driven, giving control of the amount of air circulated. Whichever method of producing the draught is used, the correct distribution of the air after entering the machine is a matter of difficulty, and one can only hope that each portion of the machine received its correct proportion of air, for the running staff have no control of the air distribution, nor of the amount of heat carried off by each separate air stream. Even should the various air currents be correctly distributed when the machine is new, deposits of dirt after use will soon alter the air distribution, and the effect of incorrect distribution of air is of serious practical importance.

Practically all machines are rated on ultimate temperatures, which implies the temperature of the hottest part of the machine on the outside of the insulation; and as a matter of fact the position of this hot part is inaccessible when working, and the temperature may or may not be revealed by thermo-couples or resistance thermometers. The temperature of the ventilation air leaving the machine indicates roughly the amount of heating of the machine, but gives neither the maximum nor the average temperature, as the temperature gradient is unknown. If the separate discharge temperatures of each air current were known, a better indication would then be obtained of the hottest part of the machine.

Suggested Lines of Improvement.

The operating engineer or user of a plant as a rule can only indicate the various features which have given him trouble, and he can suggest the parts which to him appear to require improvement. The modification of machine necessary to embrace these suggestions in practice is for the expert designer to shape. It may, of course, be practically impossible to adopt some of these suggestions, no matter how desirable they may be. However, the logical path along which improvement should lead is towards the ideal, halting as the practical limitations of present construction retard progress for the time being, and of course difficulties of present methods of construction are but the limitations of to-day.

So far, the paper has given a plain statement of the ordinary difficulties experienced with turbo-generators. The engineer is at a serious disadvantage when using such machines, for the requirements of his load compel all the plant to be worked at its maximum capacity, as spare plant during the past few years has generally been non-existent.

Such generating plant is entirely enclosed, and can neither be inspected nor its temperature easily determined under working conditions. There is also a probability that if a breakdown occurs it will result in a fire, necessitating rewinding and the shut-down of a large unit for 8 or 10 weeks. Faults which are suspected are difficult to locate, and, when located, nothing short of a complete rewind is usually of service. In fact, high-speed generating plant may offer more difficulties than almost any other kind of plant. At the same time, when the plant is quite sound it requires less attention than practically any other.

From the operating point of view, the requirements of modern turbo-generators are (1) reliability, (2) efficiency, (3) ease of operation. Reliability calls for machines which shall be fireproof, the coils of which cannot break down or overheat, the insulation of which shall not fray, crack or deteriorate, and the electrical joints of the machine shall be so constructed that there is no chance of their giving way under load. Most operating engineers would consider reliability the most important of the above conditions, and would be willing to obtain it at the sacrifice of some electrical efficiency.

Ease of operation requires some better means of knowing what is happening inside the enclosed frame of the machine. It ought to be possible to determine continuously, with some accuracy and by simple means, what is the temperature of any part of the machine, and it is desirable to anticipate breakdowns by the indication of rising temperature of the faulty part, or otherwise, before the fault develops.

The output of the machine should be independent of air temperatures and if possible there should be some reserve of capacity to meet sudden overloads. With a view to considering how these conditions may be met, the several causes of failures already mentioned will be considered and the remedy for each type of failure will be briefly discussed.

Rotor coils' centrifugal force.—The difficulties of centrifugal stress resulting in the crushing of insulation between the turns of the rotor windings and the distortion of deep narrow coils have already been indicated, and the difficulty of securing the end loops has also been mentioned. The first remedy is to manufacture a suitable insulation and is beyond the scope of this paper. When it is realized that a pressure of over 2 tons per square inch may be encountered with the insulation between and around the outer turns, and that the insulation

must stand continuously a temperature of 200° F., it will be seen that the problem is not one of easy solution. The choice of suitable insulation at present is restricted to mica and various forms of hard paper. The coil should be made of as great a width as possible, and the separate turns laid flat upon each other. The support of the coils against distortion at the end of the loops can be prevented by substantial metal packing between the loops.

The safest band over the coils would be one of drawn steel tape, which would require centering by other means than the coils themselves. This form of banding is the one used for the much more severe conditions required by the reinforcement of high-velocity gun tubes.

A flexible wire or tape band has other advantages over a solid ring; the distribution of centrifugal stress is not uniform either axially or circumferentially, and this unequal loading sets up secondary stresses in solid bands. With a laminated tape band, each turn can adjust itself to the strains upon it. The reduction in rotor diameter is a method of reducing the centrifugal stresses.

Rotor couplings.—The difficulties of flexible couplings of the claw pattern, with excessive pressure upon the line of contact, together with defects in centering and of running balance, have caused a gradual adoption of solid flange couplings.

Stator cores.—The problem of inadequate size of keys is a matter of more ample proportions, or of reversion to the original design of keys stamped out of the discs. The trouble of soft cores is usually due to the end plates being of insufficient stiffness, and as they are generally attached to the frame only at the periphery, there is a considerable spring across the face of the plate. In case of cores of considerable radial depth, one or more rings of insulated bolts may be necessary in addition, in which case all electrical contact with the bolt heads and nuts on the end plates must be carefully avoided. The bolts and nuts require countersinking to give free space for the end connections. The lack of support at the teeth is due to the narrow width of stiffening finger chosen to give the greatest area for the air current. Stronger I and ⊔ supports should be provided. Another and more complete remedy is considered later.

The remedy for soft cores resulting from inaccurate punching of the slots and keyways is obviously that of more accurate stamping.

Stator windings.—Even with the most thorough lamination of conductors, no trouble usually occurs through lack of stiffness in the portion of the coil within the winding slot, except at the very extremities of the slot where displacement of the end connections may give rise to trouble. The difficulty of obtaining a firm wrapping upon a thoroughly laminated bar has been mentioned, and the remedy would appear to be less drastic division of conductors, or a better nesting together and impregnation before wrapping.

The end connections, if attached to weak laminated stator bars, are difficult to stay adequately. Usually fibre spaced blocks are laced between the ends of the stator bars at the junction with the end connectors; these give mutual support between the bars in a circumferential direction, but stresses on the short-circuit are also radial from the centre, and in this direction the space blocks give but little support.

The remedy is to provide continuous coil supports having winding slots for the entire length of the end connectors. The terminal connections to each phase and to the neutral need not be further discussed.

Joints.—The risk of defective soldered joints has been dealt with. Soldered joints have of course the advantage of allowing easy disconnection for repairs at any time, but in the ideal machine under consideration no repairs would be necessary, and no joints would require disconnection until the generator went out of service with old age. Under these conditions all the joints would be fusion welded, except possibly in the case of the largest joints, where clamped and soldered connections would be permissible if well removed from the rotating field.

Heating and fire risks.—Owing to the limitations of air cooling, it has been argued that, provided suitable insulation can be found which will safely stand temperatures of 250° to 300° F., it is neither necessary nor desirable to limit the temperatures to lower figures. So far as is known, the only two insulating materials which can withstand such temperatures for any prolonged period without charring are mica and asbestos. As a rule, mica cannot be employed without a fibrous or paper backing on to which it is built by varnish or gums, whilst asbestos requires similar material to fill up the pores and render it suitable for insulation use. Such varnish or gums soften at temperatures approaching 300° F. The melting-point of solder if used is also an important matter; for ordinary mixtures it is about 370° F. to 390° F.

Even assuming insulation difficulties are overcome, there remains the question of thermal expansion at these high temperatures. The respective coefficients for steel and copper for one degree F. are: steel, 600×10^{-8}; copper, 955×10^{-8}. A steel rotor 80 inches long on the polar face, with a temperature rise from 60° F. to 250° F., will receive an increment of 0·0912 inch, whilst the copper coil within the rotor slot will have an increment of 0·1452 inch; that is, the copper increases beyond the steel by 0·0540 inch in the rotor length of 80 inches.*

This increase, though very small, takes place whilst the coils are subjected to severe lateral pressure, and the effect of movement under such conditions will certainly shorten the life of the insulation.

The following figures on the resistance to crushing of mica are given by Professor Miles Walker:—

"Mica (pure white) 0·010 inch thick, when tested for crushing between copper places, breaks down at 40,000 lb. per square inch owing to the flow of copper. When tested between steel plates, it will withstand 90,000 lb. per square inch."

From these figures, it would appear that the slight movement of the copper plates is sufficient to flake and destroy the mica at a very reduced mechanical pressure. The effect of the probably greater and continued movement under thermal expansion cannot be

* A temperature gradient of 50 degrees across the rotor insulation will increase this difference of increments to 0·065 inch.

otherwise than detrimental to the mechanical strength and life of the insulation.

The relation of the temperature to the useful life of the insulation is of great importance. Insulation secured in place and not subjected to mechanical stresses, such as that upon the separate turns of stationary field magnets, may be satisfactory, even when quite charred and devoid of any mechanical cohesion. With turbo-generators, the useful life of insulation practically ceases when it has mechanically failed.

The matter is briefly dealt with by Messrs. Steinmetz and Lamme.* Two curves are given, showing the relation of the useful life of insulation to the temperature, for:—

(A) Fibrous insulation, including fabric and paper; (B) mica and micanite insulation. The results have been reduced to Fahrenheit scale, and each curve has

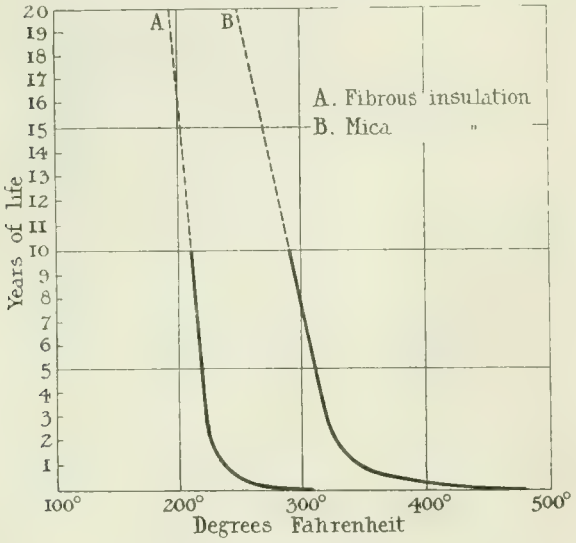


FIG. 7.—Curve of temperature and life of insulation.

been continued to a hypothetical life of 20 years (see Fig. 7). There is clear indication that a reduced temperature gives a greatly increased life. During the past 10 years long physical life of turbo-generators was not of great importance, as the continual reduction in steam consumption was sufficient to give a short economical life to turbo-generator plant. Such improvements in steam consumption are, however, now approaching a point when further considerable gains are difficult to accomplish.

It would appear that for large machines working continuously night and day for months together, a temperature of 150° F. has much to recommend it from the point of view of capacity to meet sudden overloads and long life of insulation.

Having the fire risk in view, all inflammable packing insertion and all fibrous insulation should be avoided in both stator and rotor. The ideal insulation is yet to be found, but it would have a substantial body of mica built up without inflammable gum or varnish and with some degree of flexibility. The binding material of the mica and packing must have a high thermal conductivity and suitable specific inductive capacity to give a uniform electrical pressure gradient through the mass of insulation.

These suggested improvements have been more or less introduced into the latest designs of turbo-generators, but even the best of modern machines appears to stop short of the perfect generator.

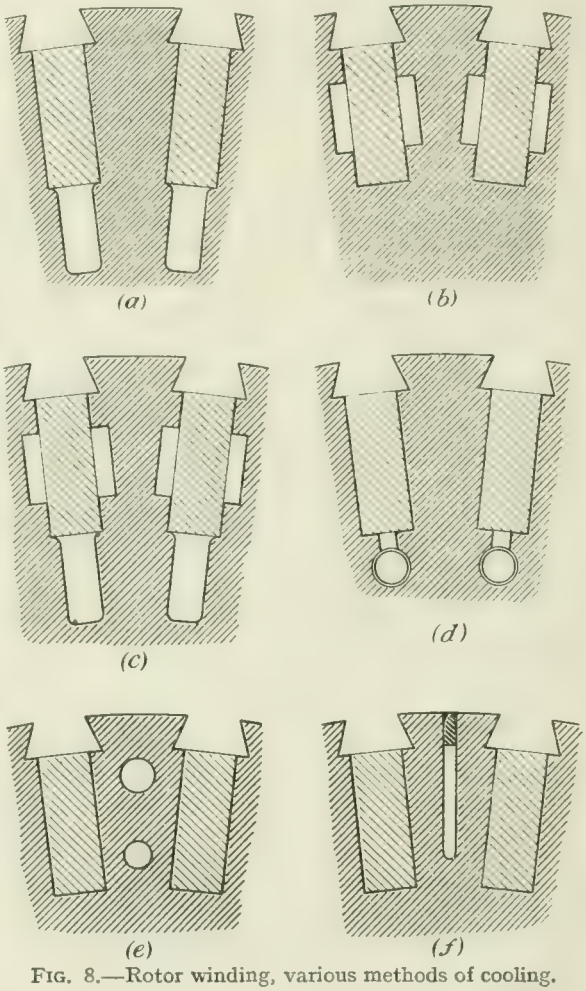


FIG. 8.—Rotor winding, various methods of cooling.
(a), (b), (c), air cooled. (d), (e), (f), water cooled.

IDEAL MACHINE.

Consideration of the usual defects already mentioned shows that air ventilation gives rise to the following difficulties:—

(1) Impossibility of equal distribution of air with presence of hot spots;
(2) Weak construction of stator, open type of end windings and serious fire risks;
(3) Larger diameter of rotor with greater centrifugal forces; inadequate cooling of end winding loops;
(4) Higher temperatures than desirable, with reduced life of insulation.

* *Transactions of the American Institute of Electrical Engineers*, vol. 32, p. 79.

The ideal machine must be free from these defects, and should also embrace the following features :—

(*a*) Coils to be continuously held against movement under mechanical forces, but free to expand with heat.
(*b*) Working temperature and output independent of air conditions.
(*c*) Capable of working at a much reduced temperature, and to be practically fireproof.

Machines constructed to embrace these features would undoubtedly be much superior to those at present manufactured, if the modifications do not introduce other difficulties either in construction or in operation.

To obtain these advantages, all windings, including rotor end loops and stator end connections, would be contained in continuous metal winding slots, with adequate freedom for expansion. The windings would be securely supported over their entire length, and the heat generated in the copper would be directly conveyed to the surrounding supporting metal, and dissipated by liquid cooling.

As a more detailed comparison of the two methods of cooling, various designs of cooling rotor windings have been drawn out for a modern high-speed rotor (Fig. 8).

Taking the ordinary air velocities in rotor ducts as 10,000 feet per minute, and a moderate water velocity of 500 feet per minute (8·3 feet per second), the relative cooling capacities of the streams of air and water are as shown in the table below.

The sizes of cooling ducts are taken as large as can be constructed with the winding slots shown, viz.

Slots, 5 in. deep × 1½ in. wide ; coil space, 4 in. deep × 1½ in. wide ; tooth width at periphery, 3 in. ; 40 in. diameter rotor.

The actual heat-abstracting powers of the two sets of conditions per degree F. rise in temperature of cooling medium for the velocities stated are :—

Air ; 1·266 therms per minute per square inch of air duct.
Water : 216 ,, ,, ,, ,, water duct.

The capacity of water over air cooling is very marked, as might be expected, and may be in excess of the capacity of the insulation to conduct the heat, a matter considered later. A rotor constructed with cooling ducts as shown in Fig. 8 (*f*) is detailed in Fig. 9, where water-cooled supports are shown for the end loops against side slip.

Arrangement	Proposed by	Size of Ducts taken on Illustration	Relative Cooling Capacity
Fig. 8 (*a*)	Ordinary arrangement	2½ in. × 1 in., one air duct	1
,, 8 (*b*)	Siemens	2 in. × ½ in., two air ducts	0·8
,, 8 (*c*)	Schuckert	2½ in. × 1 in., one air duct 2 in. × ½ in., two air ducts	1·8
,, 8 (*d*)	Parsons	1 in. water tube	54
,, 8 (*e*)	Siemens Dynamo Works	1 in. and ¾ in. water holes	83
,, 8 (*f*)	Author	3½ in. × ⅜ in. water slot	89

Various designs have been proposed using liquid cooling. Whilst the majority of them are of foreign origin the initial adaption of water cooling to modern machines is to be credited to Messrs. C. A. Parsons & Co., Ltd.

All the liquid cooling designs on record appear to deal with the problem of heat dissipation as an adjunct to air cooling. If, for the moment, the principle of liquid cooling be accepted and be completely developed as a practical feature, there are a number of important modifications which at once become possible. Air ventilation, with the difficulties of cooling and cleaning, becomes unnecessary, and the fire risk of machines largely disappears if there be no air to feed the flames. By splitting up the water paths in the machine, and by providing adjusting cocks in the water supply to each cooling device, it becomes a simple matter to determine the temperature of each part of the machine and to adjust the water flow to give a uniform temperature with elimination of hot spots, and having regard to the superior cooling effect of water over air, a lower temperature would be possible with enhanced life of the insulation.

A further and great advantage would be in the provision of continuous supports to the end connections of both stator and rotor windings, which at present are the weakest features of most generators.

Water cooling for the stator does not appear to have been developed to any great extent ; hollow water-cooled stator frames have been designed by Herr E. Huther, and I am informed that a few machines were constructed by the A.E.G. on these or similar lines, but not of recent years.

Geisenhorner, of Schenectady, proposed cooling devices of thin stamped metal for building into the stator core, but I have found no record of machines using these devices having been constructed.

In the Appendix is given a list of a few British patents illustrating the development of air and water cooling.

Combination of Water Cooling and Coil Supports.

If full advantage is to be taken of water cooling, it would appear desirable for the cooling arrangements to be in close proximity to the coils, with very low resistance heat paths, and to serve the double purpose of coolers and coil supports. Designs have been developed by the author upon these lines, and are indicated in diagram form in Figs. 8 (*f*), 9, 10, 11, 12 (*a*) and (*b*), and 13.

A short description of each may be of interest.

In Fig. 8 (*f*) the heat from the rotor coils is directly transmitted to the iron tooth, which would be made slightly wider than usual to compensate for the loss in section where the water duct is milled out of the solid tooth; the top of the duct is closed by a steel plug, fusion welded in place.

either at the flanged coupling as in Fig. 13, or could be continued through the turbine rotor shaft to the water sealing gland at the low-pressure end of the turbine.

Fig. 10 is a section of the stator with two types of coil supports, one for the end windings and fixed at the ends of the core, and the other built into the core

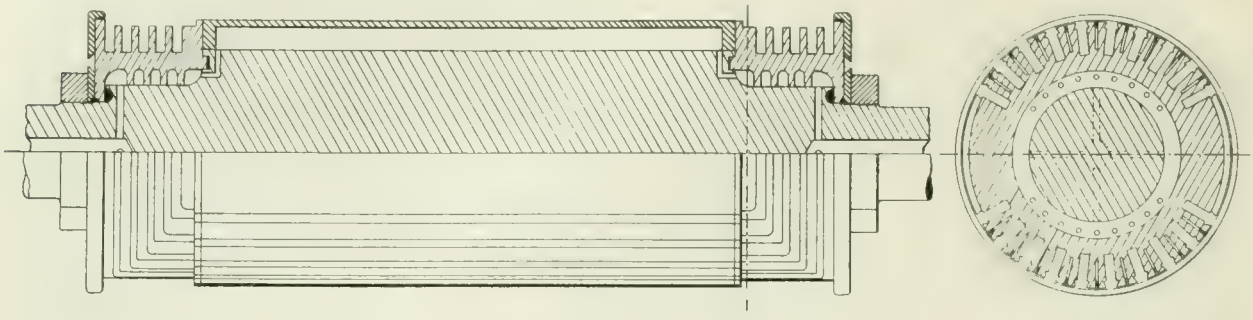


FIG. 9.—Rotor with separate coil supports, water-cooled.

Fig. 9 shows a rotor with teeth cooled as described, and provided with separate bronze coil supports at each end of the core. The supports would provide continuous slots for the end loops of the rotor coils. The metal teeth between the coils give substantial support at the rotor periphery for supporting and centering flexible steel tape bands. The steel ring over

between batches of laminations. This latter support is constructed with the inner part laminated to reduce eddy currents, and yet of considerable strength to clamp the portions of the stator bars it embraces and gives considerable stiffness to the core teeth. The hollow interior is divided by a diaphragm into flow and return water passages.

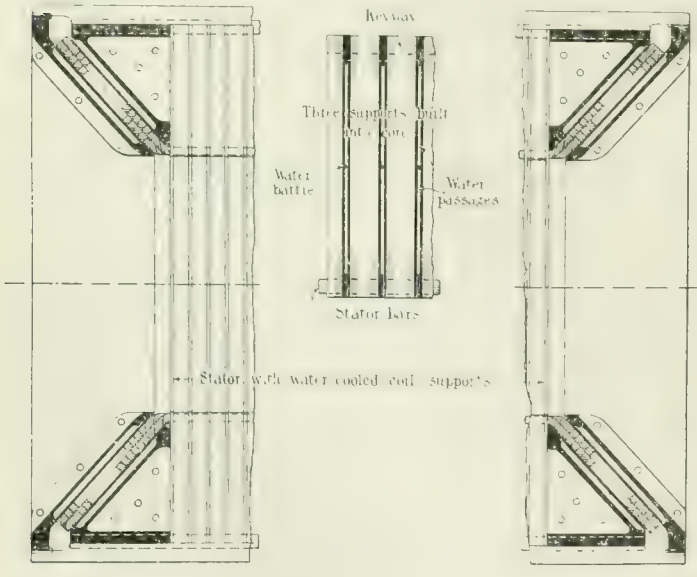


FIG 10.—Stator with water-cooled coil supports.

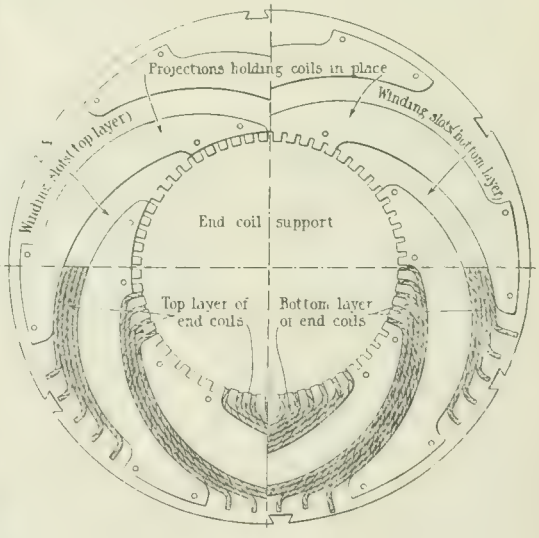

Projections holding coils in place
Winding slots (top layer)
Winding slots (bottom layer)
End coil support
Top layer of end coils
Bottom layer of end coils

FIG. 11.—Details of water-cooled end-coil supports.

the end flange is arranged to give a mechanical anchor for the end of the steel binding tape.

The water path is along the shaft from beyond the exciter with helical flow under the cooling support for the end loops, along the hollow teeth to the other end of the rotor, helically under the second support for the end loops. The water discharge could be arranged

The two pairs of end-coil supports at the ends of the stator are shown in section with the two layers of end connections clamped between them.

Fig. 11 shows an end elevation of the stator end (inner) coil support, the bottom quadrants of which illustrate respectively the under and upper layers of the end windings. The two upper quadrants show

the supports without windings, and with the clamping projections in place, forming between pairs of them the winding recesses for a group of end connections, one bar per slot winding.

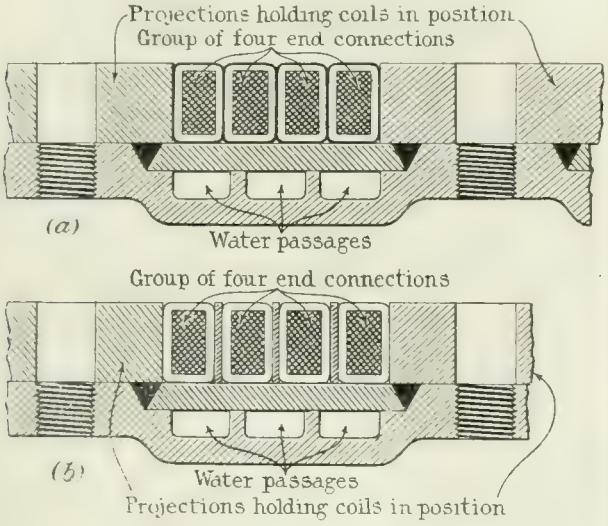


FIG. 12.—Details of water-cooled winding slot on end stator support.

(a) With copper tapes as heat conductors.
(b) With metal fins as heat conductors.

Fig. 12 (*a*) is a part section of such a winding recess, with four end connections in place, and supported by the projection on each side.

Fig. 12 (*b*) is a similar section, but showing metal fins between each conductor, giving a low resistance heat path to the liquid.

As the metal of the coils supports must of necessity be in close proximity to the active conductors, precautions are necessary to reduce stray currents, whilst retaining a strong construction.

Figs. 12 (*a*) and 12 (*b*) show the coils clamped directly over a water cooling duct cast in the support and enclosed by a metal plate fusion welded in place. The plate must have considerable mechanical strength and high electrical resistance.

Copper-nickel alloys are on the market, which are as strong as high-quality bronze, and have over 20 times the electrical resistance of copper. Their use would reduce the stray currents to a comparatively insignificant loss.

WATER COOLING.

When arranging the water circulating system, due regard must be paid to the risk of corrosion and to the recommendations of the Corrosion Committee of the Institute of Metals, viz.—

(1) Only clear water to be used,
(2) Water to be free from gases in suspension or solution.
(3) Water must be neutral, or only very slightly alkaline.

To comply conveniently with these recommendations, the cooling water is taken from the condensate of the steam turbine, forced by the extraction pump through the cooling devices of the alternator and discharged

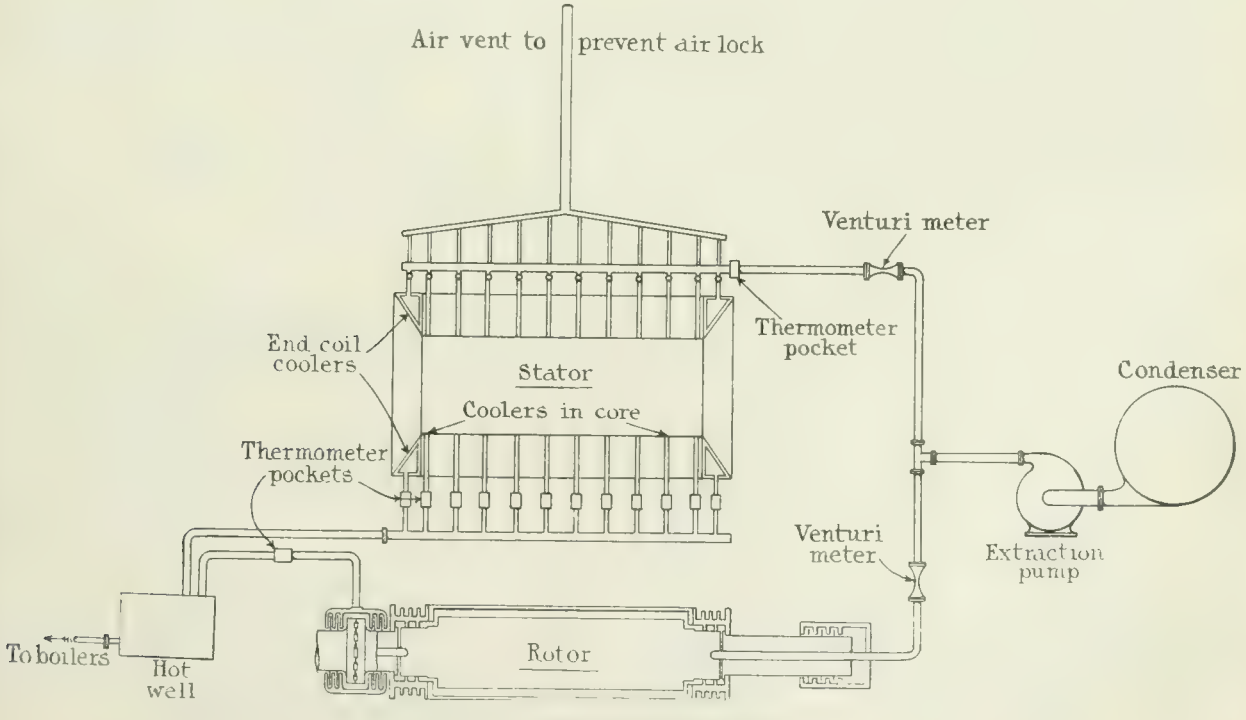


FIG 13.—Diagram of water cooling.

into the turbine hotwell. The whole of the heat losses in the alternator would then be utilized. With modern high vacua the temperature of the condensate is from 70° to 80° F., which temperature would then receive an increment of from 13 to 15 degrees F.

The return flow of each water path is shown provided with a thermometer pocket, and by reducing the flow in any particular cooler a close indication of the maximum local temperature can be obtained.

The object aimed at in all the designs described is to interleave the conductors with liquid-cooled supports, thus providing continuous winding slots for the coils, coil loops and end connections, etc., in which the weakest and most frail bar (no matter how thoroughly the bar be laminated) is continuously supported under the most severe short-circuit conditions. At the same time, freedom for expansion is provided, together with low-resistance heat paths to the cooling medium.

As every portion of stator and rotor windings would be enclosed in cool metal winding slots of necessity, the cooling would be much improved and the fire risks practically eliminated. The absence of ventilating ducts in the stator would be the immediate gain of solid cores and firm support over the entire surface of the stator teeth.

It might be thought that the difficulties of station engineers are sufficient without increasing them by the adoption of water cooling of generators with the attendant risk of water leakage. If the present designs of large alternators were perfect it would of course be folly to suggest any change, but it must be admitted that improvements in design are desirable.

It remains to be shown that the modifications proposed, while removing certain difficulties, do not give rise to others which are greater.

The problem in the plainest terms is the possibility of constructing stator cooling devices capable of withstanding a water temperature of about 120° F. and a pressure of 50 lb. or less per square inch, whilst at the same time the devices must have sufficient strength to withstand the short-circuit stresses on the stator. The rotor cooling devices are subjected only to the internal water pressure and stresses resulting from centrifugal forces. Adequate mechanical strength can be given to these devices by the use of suitable material, proportioned in accordance with well-known methods now used in all branches of engineering industry.

With respect to the prevention of water leakage, all joints can be constructed of a character similar to those used in hydraulic practice, and dealing with pressures of over 2 tons per square inch, or in accordance with steam practice, with high-pressure superheated steam of 300 lb. pressure per square inch and a temperature of 700° F. Fusion welding is now an accepted construction for the more arduous requirements of high-pressure boilers and steam piping. Moreover, the fusion-welded water joints may be designed so that the weld is subjected to no other stresses than those caused by the internal water pressure. Consequently, combining skilful design, stout construction and reliable workmanship, one can ensure no movement of the coils, no leakage of the water devices, and no overheating of the coils. Under such conditions, failure of machines should be infrequent. Should, however, a short-circuit in a machine occur, the walls of the cooling ducts may become fused, in which extreme case a jet of water would immediately flood the machine; but even so, this flooding by water would only occur after a burn-out had happened, and in such circumstances a stream of water playing upon the fire would certainly be better than a fierce blast of air. In all cases, prevention is better than the best remedy, and the improvements suggested are all of preventive character.

It will be seen, therefore, that whilst water cooling will remove many if not all of the risks inherent in the ordinary air-cooled machine, there is nothing in its application that presents any real difficulty or introduces any method of construction which has not been established in other branches of engineering.

General Comparison of Air and Water Cooling.

In modern turbo-generators of large capacity, over 95 per cent of the heat is carried off by the ventilating air. Assuming for simplicity that all the losses are dissipated by either air or water circulated through the machines, the relative quantities of each can be calculated from the following data:—

J = mechanical equivalent of heat, taken as 778 foot-lb.
1 kw. hour = 3,412 therms.
,, minute = 56·82 ,,
Specific heat of air = 0·237.
,, ,, ,, water = 1·0.
Weight of 1 cub. ft. of air
= 1/13 lb. at 60° F. and 30 in. barometer.
Weight of 1 cub. ft. of water = 62·35 lb. at 60° F.
Comparative cooling effect of

$$\frac{\text{1 cub. ft. of water}}{\text{1 cub. ft. of air}} = \frac{62{\cdot}35}{0{\cdot}237 \div 13} = 3{,}420.$$

Max. velocity of air in external air ducts, say 1,500 ft. per min.
Max. velocity of water in external water pipes, say 200 ft. per min.
Allowing a temperature rise of 50 degrees F. for both air and water:—
Amount of air required per min. for 1 kw. loss

$$= \frac{56{\cdot}82 \times 13}{0{\cdot}237 \times 50} = 62{\cdot}34 \text{ cub. ft.}$$

To allow for air short-circuited or not properly distributed, say 100 cub. ft. per min.
Area of external air duct per 1 kw. loss

$$= \frac{100}{1{,}500} = 0{\cdot}066 \text{ sq. ft.}$$
$$= 0{\cdot}95 \text{ sq. in.}$$

Amount of water required per min. for 1 kw. loss

$$= \frac{56{\cdot}82 \text{ lb.}}{50} = 1{\cdot}135 \text{ lb.}$$

To allow for unequal distribution of water, say 1·5 lb or 0·15 gall. per min.
Area of external water supply pipe per 1 kw. loss

$$= \frac{0{\cdot}15 \times 0{\cdot}16 \times 144}{200} = 0{\cdot}00173 \text{ sq. in.}$$

$$\frac{\text{Area of external air duct}}{\text{Area of external water duct}} = \frac{0{\cdot}95}{0{\cdot}00173} = 550.$$

The losses in turbo-generators differ with various designs, but representative figures are given below, together with the relative amounts of air and water necessary for cooling on the liberal scale just worked out.

On the assumption that the condensate be used for cooling the proportion necessary to limit the rise to 50 degrees F. is given, also the increment of hotwell temperature.

Size of Alternator, kw.	Internal Loss, Per cent	Quantity of Cooling Media: Air	Quantity of Cooling Media: Water		Size of External Ducts: Air		Size of External Ducts: Water	Per cent of Condensate for 50 deg. Rise	Increase of Hotwell Temperature
		Cub. ft. per Min.	Cub. ft. per Minute	Gallons per Minute	Sq. in.	Diameter	Diameter		
5,000	5·5	27,500	6·6	41·2	18	5 ft	$2\frac{1}{2}$ in.	41	15·5 deg.
10,000	5·0	50,000	12·0	75	33	6 ft. 6 in.	$3\frac{1}{2}$ in.	39	15·0 deg.
20,000	4·5	90,000	21·6	135	59	8 ft. 9 in.	$4\frac{1}{2}$ in.	36	13·5 deg.
50,000	4·0	200,000	48·2	300	133	13 ft.	$6\frac{3}{4}$ in.	32	12·5 deg.

The relative cooling capacities of the *internal* stator ducts of equal volume would be :—

Water ducts with water velocities of 500 ft. per min.
Air ducts with air velocity of 4,000 ft. per min. 420.

This increased potential capacity for cooling might be in excess of the capabilities of the remainder of the machine to transmit the heat to the cooling ducts through the insulation around the copper.

The laws of thermal conductivity are very similar to Ohm's law and may be stated thus :—

A (heat) current passing through a (thermal) resistance gives rise to a difference of pressure (temperature) across the resistance. In other words a hot insulated conductor passing heat through the insulation is always hotter inside the insulation than on the outer surface of the insulation being cooled. As the interior surface of the insulation must never exceed the safe temperature of the insulation, no matter how cold be the outside of the insulation, a limit to the maximum heat flow through the insulation is soon reached.

The thickness of insulation usually lies between 0·1 and 0·2 inch, and the transference of heat measured in watts per square inch for various kinds of insulation is given below for heat gradients of 50 and 100 degrees F. For comparison the corresponding figures are also given for still air (without convection) and for copper.*

TABLE GIVING HEAT DENSITY IN WATTS PER SQUARE INCH OF CONDUCTING AREA FOR VARIOUS TEMPERATURE GRADIENTS, AND FOR HEAT PATHS 0·10 AND 0·20 INCH LONG.

Class of Heat Conductor including Ordinary Insulation Copper and Air Cells	Heat Density in Watts per Square Inch: Gradient 1 deg. F.		Gradient, 50 deg. F.		Gradient, 100 deg. F.	
	0·10 in. Path	0·20 in. Path	0·10 in. Path	0·20 in. Path	0·10 in. Path	0·20 in. Path
Copper	45	22·5	2250	1125	4500	2250
Mica plates without air spaces ..	0·0508	0·0254	2·54	1·27	5·08	2·54
Empire cloth and mica in alternate layers tightly wrapped	0·0295	0·0147	1·47	0·735	2·95	1·47
Empire cloth and mica in alternate layers with usual air spaces ..	0·0206	0·0103	1·030	0·515	2·06	1·03
Micanite, with 11 per cent shellac as binding material	0·0172	0·0086	0·86	0·43	1·72	0·86
Still air (air cells)	0·0028	0·0014	0·14	0·07	0·28	0·14

For example, a stator coil with insulation 0·10 inch thick has an outside temperature of 100° F., and is insulated with micanite built up with 11 per cent shellac. If the inside temperature is not to exceed 150° F. the

* H. D. SYMONS and M. WALKER : *Journal I.E.E.*, 1912, vol. 48, p. 682.

temperature gradient must be 50 degrees F. or less; to be within that figure, the heat density must not exceed 0·86 watt per square inch of that portion of the insulation which is conducting away the heat.

In the case of the rotor coil shown in Fig. 8 (*f*) all four faces of the insulated coil may be considered to be effective heat conductors.

With water-cooled stator end connections having several conductors in the same winding recess (Fig. 12*a*) only one face is usually in contact with the cooling device, and the other three faces of insulation are not freely conducting. The thermal conductivity can be improved by wrapping copper foil around the coil giving a direct heat path from all four faces. The conductivity of copper to micanite (11 per cent shellac) is 2600 : 1.

In the case of iron losses, each cooling element is in direct contact with groups of stampings, and the heat path is both small in length and considerable in area.

(2) In extremely dirty and sulphurous atmospheric conditions.
(3) At high altitudes with reduced air density.
(4) On board ship, where air cannot be freed from salt spray.

As an example of turbo-generators working at high altitudes, the stations on the Rand may be cited. At an elevation of 6,000 feet and a barometer of 24·5 inches * the air density would be 82 per cent of normal, and a standard turbo-generator frame of 10,000 k.v.a. would only be suitable for an output of approximately 8,500 k.v.a. air cooled. The same frame if adapted for water cooling would probably give an output of 12,500 k.v.a.

Consequent upon the higher ambient temperature of the South African climate, water cooling would have the further advantage of a much lower average temperature of windings.

The last case deserves detailed consideration.

Class of Ship	Displacement	Length	Speed	Shaft, h.p.	Generators: Cooling Air: Cub. ft. per Min.	Generators: Cooling Air: Air Duct Area	Generators: Cooling Air: Diam.	Generators: Cooling Water: Galls. per Min.	Generators: Cooling Water: Diam., Pipe	Motors: Cooling Air: Cub. ft. per Min.	Motors: Cooling Air: Air Duct Area	Motors: Cooling Air: Diam.	Motors: Cooling Water: Galls. per Min.	Motors: Cooling Water: Diam., Pipe
	Tons	Ft.	Knots	Approx.		Sq. ft.	Ft.		In.		Sq. ft.	Ft.		In.
Tramp	13,500	420	10	2,500	12,000	6	2·8	18	$1\frac{3}{4}$	11,000	$5\frac{1}{2}$	2·8	16·5	$1\frac{1}{2}$
Intermediate ..	17,500	500	14	10,000	45,000	$22\frac{1}{2}$	5·4	67·5	$3\frac{1}{4}$	40,000	20	5·0	60	3
First-class passenger	20,000	550	19	21,000	85,000	$42\frac{1}{2}$	7·4	128	$4\frac{1}{4}$	78,000	39	7·0	117	$4\frac{1}{8}$
First-class Atlantic liner	33,000	760	25	68,000	250,000	125	12·8	375	$7\frac{1}{2}$	225,000	$112\frac{1}{2}$	12·0	338	7
Small cruiser ..	3,500	400	30	40,000	165,000	$82\frac{1}{2}$	10·3	250	6	150,000	75	9·9	225	$5\frac{3}{4}$
Super "Dreadnought"	25,000	600	25	27,500	115,000	$57\frac{1}{2}$	8·7	170	5	100,000	50	8·0	155	$4\frac{3}{4}$
Battle cruiser ..	33,000	860	35	180,000	600,000	300	19·6	900	$11\frac{1}{2}$	550,000	275	18·0	825	11

Velocity in external air ducts taken at 2,000 ft. per min.
,, ,, water pipes taken at 200 ft. per min.

The cooling effect of water is so considerable that without certain precautions, condensation difficulties may arise. If the temperature of the cooling devices falls below the dew point atmospheric condensation upon them will take place. This can be avoided by using cooling water with an inlet temperature higher than the dew point, as by the method shown in Fig. 13.

As the output of most machines is rated by ultimate temperature, there are substantial grounds for concluding that water cooling will allow an increase in output for the same total weight and volume of 25 to 33 per cent. Some readjustment of relative copper and iron losses may be necessary, and the result should be a substantial reduction of average temperatures and weight for the same output. Whether water cooling will displace air cooling time alone can prove.

There are, however, a number of cases where water cooling offers advantages over air cooling, quite apart from the improved and more robust construction of machines, i.e. for machines working under the following conditions—

(1) In hot climates where cool air is difficult to obtain.

Ship Propulsion.

The field for the electrical propulsion of ships is practically virgin and immense in size.

In order to gauge the size of the power problem involved, the particulars of various representative classes of ships are given, taken from published figures. From them the relative quantities of cooling air and cooling water are calculated. The generators are assumed to have the losses already given for land service. The motors may be either high-speed machines geared down to the propeller shafts, or low-speed direct coupled. In either case the same internal losses have been assumed, and these will be sufficiently accurate for the present rough examination. If the motors were low-speed, direct coupled to the propeller shafts, they would be of open-type construction; of necessity they would be housed in small watertight compartments and, so far as ventilation is concerned, may be considered to be enclosed machines requiring auxiliary cooling, except for the smaller powers.

The electric power would be either two-phase or three-phase, with a pressure of approximately 1,000

* J. H. Rider: *Journal I.E.E.*, 1915 vol. 53 p. 629.

volts for small ships, increasing to about 10,000 volts for the larger powers, otherwise the size of the conductors and operating switchgear would be too heavy and costly.

The one great difficulty with even low-pressure electrical plant for ship work is the presence of salt water. Electrical apparatus quite suitable for land service usually requires modification to suit sea conditions and, up to the present, high-tension apparatus of any considerable power has not been used to any extent under severe sea conditions.

The difficulties peculiar to sea service are due to the extreme weather conditions encountered. In the course of a voyage a ship may meet air temperatures varying from 0° F. to 100° F., and must of necessity develop full power continuously under extreme Red Sea summer conditions, with day temperatures of 105° to 115° F. falling at night to 95° F.

Again during heavy gales waves may sweep the ship from end to end, with spray continually blown over the tops of the funnels. Such rough conditions may continue during an entire Atlantic voyage, and the salt water finds its way into practically every part of the ship.

It is difficult to see how the cooling air can then be collected in large volumes free from salt spray. Air washing might get rid of the larger portion of the salt, but its operation in frosty weather would be difficult, and plant difficult to operate is not required at sea.

Apart from operating troubles, the question of room must be considered.

The sizes of air ducts are calculated for a high velocity of 2,000 feet per minute. They are of considerable dimensions, and it is doubtful if any shipowner would sacrifice valuable carrying space to accommodate them. The situation of the generators and motors would be aft of midships, and short vertical air ducts to them would cut through state-rooms and saloons of liners, the most valuable portions of the ship.

In fighting ships the problem is more difficult, as the powers to be developed are higher and the space is enormously costly. At present the floor space allowed for steam propulsion, including boilers, engines, auxiliaries and working gangways is generally at the rate of 10 h.p. per square foot—a figure quite unapproached in land service.

Owing to the low free-board, all cooling air would require to be collected at some height above the deck to ensure that the air was even moderately free from spray in heavy weather. Such elevated air trunks might seriously interfere with the training and firing of the guns from the aft turrets, and there would be the further complication of piercing watertight bulkheads and cutting various protective decks. The objections, in fact, might be so serious as to outweigh any advantages of electric propulsion.

With water cooling, the difficulties of collecting and conveying the cooling medium disappear, and its use presents neither the difficulties of large ducts nor the trouble of filtration.

Proposals have been made to re-circulate the air through a closed pipe system with air coolers; the sizes of air ducts are so considerable that room for them could not be found with the present allowance of engine-room space. There is now usually considerable difficulty in finding room for the comparatively small steam pipes and valves.

Whether the machine be air cooled or not, a certain amount of salt is likely to reach the windings, and, with pressures of 1,000 volts and over, watertight windings would be a great advantage. The micanite wrap on the stator bars may be considered to be waterproof without further treatment, but a waterproof seal over the end insulated joints is desirable. A substantial seal of vulcanized rubber could be "cured" in place over the insulated joints using the cooling devices as heaters, by passing low-pressure steam through those which embrace the ends of the stator bars.

This waterproof treatment of the stator joints would be of advantage if surface condensation took place. The ideal alternator for marine purposes should be capable of being cleaned down with a hose pipe.

The difficulties of sea conditions have in no way been exaggerated, and most of them can be overcome by adapting designs to suit sea conditions. If electrical propulsion is to progress, the problem must be attacked in a thoroughly practical way, as electrical methods will be in opposition to established interests and in competition with thoroughly sound and well-tried steam plant evolved after years of practical sea experience.

The present design of high-speed marine turbine drive is through double-reduction helical gears of fine pitch, with end-thrusts balanced by mounting pairs of helical gears with opposite angular leads. With the most perfect machining and fitting possible, the driving faces can only have lines of contact, and with the finest chrome steel gears and lubricated faces heavy drives with only lines of contacts cannot be considered to be a final solution.

Up to the present, marine turbines are not generally supplied with superheated steam, which is in striking contrast to land practice.

Conclusion.

The first portion of the paper briefly reviews the chief causes of failure of turbo-generators as now constructed, and the statements will no doubt be endorsed by most engineers who have had charge of large plant.

Designs have now passed the initial difficulties of electrical and magnetic characteristics, and the secondary difficulties of mechanical strength, durability, heating and fire risk remain.

Whether we like the idea of liquid cooling or not, the question has to be faced in the immediate future, and the full consideration of its uses gives an opportunity of considering alternator design from a new point of view. The designs described offer the following advantages over air-cooled machines.

Rotor.

(1) Smaller diameter with reduced centrifugal stresses.
(2) Mechanical support to end winding loops and steel tape bands.
(3) Efficient heat paths, low working temperature, less fire risk, and longer life.

Stator.

(4) Solidly supported core and teeth with reduction of vibration.
(5) Continuous mechanical support to windings.
(6) Efficient heat paths, low working temperature, less fire risk and longer life.
(7) Adjustment of amount of cooling to every portion, with elimination of hot spots.

The physical life of any plant, apart from breakdowns, is determined by the wear of moving parts, fatigue of such other parts as may be subjected to fluctuating stresses or, in the case of insulation, by prolonged heating combined with mechanical stresses.

Having regard to the necessarily few moving and wearing parts of a turbo-generator, viz. journals, bearings, and slip-rings, there appears to be no sound reason why it should not have as long a physical life as the low-speed plant it has superseded, provided it be possible to construct machines which do not overheat, the coils of which are efficiently and continuously supported against all stresses and vibration, and that the fire risk be removed.

If the arguments put forward in the paper are sound, machines can be constructed embracing those features, and with machines so constructed a much longer physical life may be anticipated. With dear money and expensive plant, longer physical life will be an economical necessity of the immediate future.

The latter part of the paper indicates certain specific applications of electrical power where present methods of construction should be modified to overcome successfully special conditions of working, and where it would appear that air cooling must give place to a more suitable cooling medium. Power engineering has become very largely the province of electrical engineers. If electrical plant can be made more mechanical and reliable there is every prospect of that province rapidly extending to every branch, but the fight with established practice will be strenuous.

The author anticipates that the proposal to substitute water cooling for air cooling will be subjected to adverse criticism. All new ideas must of necessity be so treated; at the same time without novelty there can be no progress.

APPENDIX.

List of a Few British Patents Illustrating Developments of Turbo-Alternators.

Patent No.	Year	Patentees	Short Description of Salient Features
2,321	1879	J. D. F. Andrews	Hollow armatures with fans for forced ventilation
23,366	1900	W. Whiteley	Water jackets on outside of frames
13,108	1905	Sir C. A. Parsons	Copper gauze around conductors to give improved heat path
20,990	1905	B.T.H.	Hollow conductors on rotors of induction rotors for circulation of cooling liquids
25,000	1905	S. Von Ammon	Air or liquid passages built into stator of induction motors for cooling
1,068	1906	Sir C. A. Parsons	Interlacing good heat conductors between active windings for magnets
28,192	1906	W. Deacon	Ventilating grids of expanded metal for stator cores
24,751	1906	Siemens Schuckert	Liquid cooling under commutators of direct-current machines
1,679	1909	M. Kloss	Rotor windings cooled by interlacing metal strips leading into air spaces below winding slots
7,203	1909	Brown, Boveri	Cooling enclosed motors by circulating air from machine through external water coolers
9,133	1909	Mavor & Coulson	Hollow tubes spaced inside enclosed motors for circulation of cooling liquids
16,457	1909	M. Haefely	Mica wrapping machines
18,151	1910		
22,789	1909	Siemens Bros. Dynamo Works	Armatures with hollow shells through which cooling liquids are circulated
20,491	1910		
1,404	1910	M. Kloss	Cooling plates between turns of active windings, also metal containers for windings to provide heat paths
14,125	1910	A.E.G.	Separate rotor teeth of steel stampings with spaces at intervals for air ventilation
14,862	1910		
14,680	1910	Sir C. A. Parsons & Low	Securing end loops of rotors by bolts whose heads are held in T slots
30,233	1910	B.T.H.	Rotor formed of stampings with air spaces at intervals, air entering at polar faces and discharging between the windings
5,247	1911	Siemens Schuckert	Air ventilation slots formed at sides and bottom of rotor winding slots
17,110	1911	E. Huther	External water-jacketed stator frame with internal radiating webs for cooling ventilating air
19,760	1911	F. G. Baum	Ventilating air saturated with water vapour, temperature above dew point

APPENDIX—*continued.*

Patent No.	Year	Patentees	Short Description of Salient Features
17,391	1912	M. A. McLean	Supports for end loops of rotor coils made of steel discs
19,792	1912	Mower & Hale	Spray washers for cleaning ventilating air
21,822	1912	Siemens Bros. Dynamo Works & Kieffer	Hollow conductors forming passages for ventilating air
6,036	1913	Brown, Boveri	Lamination of stator bars
6,647	1913	Siemens Bros. Dynamo Works	Mica wrapping machine
7,600	1913	B.T.H. & Clough & Dunker	Lamination of stator bars
10,608	1913	A.E.G.	Lamination of stator bars
10,919	1913	B.T.H. & H. W. Taylor	Lamination of stator bars
24,450	1913	A.E.G.	Damper for diverting air from cloth filter when filtering cloth catches fire
5,828	1914	Siemens Schuckert	Hollow rotor teeth for passage of cooling air
15,585	1914	Sir C. A. Parsons	Subdivision of air passages in stator frame
15,958	1914	Siemens Bros. Dymano Works & E. O. Kieffer	Method of supporting stator end connections
16,590	1914	Siemens Bros. Dynamo Works & E. O. Kieffer	Liquid-cooled rotors
16,979	1914	Siemens Bros. Dynamo Works & E. O. Kieffer	Liquid-cooled rotors
16,986	1914	Siemens Bros. Dynamo Works & E. O. Kieffer	Liquid-cooled rotors
16,980	1914	Sir C. A. Parsons	Liquid-cooled rotors
18,281	1914	G. A. Juhlin	Metal deflectors for cooling slots of rotors
19,042	1914	B.T.H.	Electric welding of rotor bars
22,950	1914	A.E.G.	Using washed air mixed with portion of heated air discharged from machine, for cooling
4,560	1915	British Westinghouse	Prevention of vibration of stator core teeth
16,464	1915	Eborall & Brown, Boveri	Keys or bolts through stator stampings connected together by copper rings to allow higher induction in core
112,930	1916	Siemens Schuckert	Baffles to air inlet of electrical apparatus to prevent entry of sea spray
103,317	1917	B.T.H.	Stator bars with multiple laminated conductors; successive turns crossed where connected at ends of stator bars
104,250	1917	B.T.H.	Arrangement of multiple fans and air ducts to each to give better distribution of air
109,294	1917	J. Shepherd	Water-cooled coil supports
110,915	1917	Electromotors Ltd.	Ventilating air from enclosed motors cooled by external coolers
116,886	1917	K. Kobukara	Enclosed squirrel-cage motors with water cooling inside motor casing, water kept out of air-gap by air under pressure
118,000	1917	Burleigh	Enclosed motors with external air coolers cooled with air or water
121,218	1918	G. A. Juhlin & J. S. Peck	Electrically closed damper to air supply to generators, operated by generator relays
120,653	1919	Vickers Ltd. & S. F. Barclay	Solid band with flange centered on rotor body
125,673	1919	Vickers Ltd. & S. F. Barclay	Machines arranged with separate air currents, axial current in rotor, axial and radial for stator
125,681	1919	S. F. Barclay	Air washers of spray pattern with electrified plates attracting dust particles
128,330	1919	B. Longbottom & E. Greenhalgh	External air coolers
128,739	1919	S. F. Barclay & Vickers Ltd.	"Hair-pin" formed coils for cylindrical rotors, fourth side connected by fusion welding
129,094	1919	J. Shepherd	Water-cooled coil supports for stator coils
129,788	1919	Kuyser & British Westinghouse	Laminated stator coils twisted within the winding slots
131,185	1919	B. Longbottom & E. Greenhalgh	External air coolers, cooled by water spray
135,122	1919	J. Shepherd	Water-cooled coil supports for rotor coils

Discussion before The Institution, 8 January, 1920.

Mr. A. B. Field: It is very refreshing to have a paper like this on design from a point of view so essentially practical. The operating engineer need show none of the reticence about talking freely of troubles and breakdowns which possibly the manufacturing engineer might feel. The manufacturer must admit, however, that the author has good grounds for his indictment in respect of some of the older machines; further, that some of the disadvantageous features which he mentions still persist, and will persist for some time. Their elimination is awaiting the development of collateral problems. Many solutions of these difficulties, some of which the author has outlined, have long been in mind, but are not immediately applicable, pending such development. For instance, many of the author's proposals presuppose improvements in methods of insulating. The main feature of the author's proposals is water-cooling, both of the stator and of the rotor. Personally, I feel that air-cooling of the machine will certainly be superseded on the biggest units in the future, that is to say, the method according to which the cooling is effected by the intake and rejection of large volumes of air per minute. Perhaps the author has hardly appreciated the possibilities of water-cooling a machine by circulating air within the machine and through an air cooler incorporated in the machine itself. This arrangement overcomes the difficulty of air ducts, air filtration, salt-laden air, and so on. It certainly is not a final solution for the biggest machines, but I believe it has a greater possibility than the author seems to assign to it. There are a great many difficulties that will arise in the author's proposals. Referring briefly to the case of the stator, the proposal to imbed completely the winding throughout its whole turn is one that has been kept in mind for many years, and attempts have been made several times to approach nearer to this condition. One such attempt I described before this Institution a few years ago.* But the real difficulty is in bringing earthed metal up against the coil throughout the entire turn. There are several places in the stator turn where the insulation cannot be as good as in the slot part. Where we have a sharp radius of curvature, or a junction between two types of insulation, we usually have to allow a considerable creepage distance; where we have connectors we cannot bring earthed metal close. For this reason (and many more) the author's proposals will have to await improvements in methods of insulation, etc. Personally, I believe that 15 years hence the machines of to-day will appear as antiquated as the 1904 machine does now, and I do not agree with the author that we ought now to be figuring upon a greater length of economical life before "antiquation" becomes effective, than we now recognize should have been figured upon 15 years ago. We need to follow much more freely the example of "scrapping" set by the Manhattan Elevated Railway generating station in New York in 1913. I think many of the points aimed at by the author will be gained finally, but not just yet, and not very closely along the lines of the author's proposals.

(*Communicated*): In view of the discussion at Manchester, and Professor Walker's endorsement there of the author's contention that a high-resistance alloy would be necessary for any metallic stator-coil supports, it seems worth while to raise the question of going to the opposite extreme. It seems at least possible that by using high-conductivity metal, suitably disposed, for such a system of coil supports (when these become practicable) stray load losses might be reduced to an extent which would much more than compensate for the losses introduced in the high-conductivity metal added. It should be borne in mind that the magnitude of the currents which can be generated in these coil supports is limited to something less than an optical image of the system of currents in the stator end-connections, and that when the coil-support currents approximate to such figures, similar currents will have been eliminated from iron and steel parts, where their presence entails much greater losses than in *non-magnetic* and high-conductivity material.

Mr. E. W. Dickinson: I have read the paper with care but have had some little difficulty in understanding exactly what the author sets out to prove. I take it that the paper is intended to bring us to the conclusion that the water-cooling of turbo-generators will overcome all our difficulties, or ought in time to do so. If that is what the author means, I am afraid I can hardly agree with him, and from what I can judge of the suggestions put forward, I am inclined to agree with the last speaker that it will be some little time before a water-cooled turbo-generator is made capable of running continuously without breakdown or serious disaster. With regard to the breakdowns experienced with present generators, I can endorse fully what the author has said as to their actual occurrence. He suggests the use of solid metal tape instead of binding wire for enclosing the end turns on high-speed rotors. I am inclined to think that the disadvantages of steel tape will be found to be as great as those of binding wire. I think experience has shown the advisability of using solid end-rings for enclosing rotor end-windings; because, should a short-circuit occur on the end turns, the separation and breaking away of the binding wire, with the consequent danger of wiping out the stator end-turns, is not then present. The author also mentions coupling troubles. My experience in that connection is that solid couplings have proved much better than flexible couplings on impulse-type turbo-generators with short stiff shafts. The author also mentions loose core plates. Many instances have been noted in this connection both in the middle and at the end of the stator cores. I think these difficulties will be overcome, as in most other cases of failure the author mentions, by careful inspection and workmanship during manufacture, whether the design be for air-cooled or water-cooled generators. This difficulty of workmanship is one of

* A. B. Field: "Some Difficulties of Design of High-Speed Generators," *Journal I.E.E.*, 1916, vol. 54, p. 65.

the greatest troubles we are up against at the present time in this country. Craftsmanship has suffered severely during the war, and we are beginning to feel the result now that the war is over. I cannot therefore agree that the inference which the author draws, that difficulties in connection with defects and breakdowns experienced on air-cooled turbo-generators cannot be overcome without resort to water-cooling, is correct. In any case I should not wish, as an operating engineer, to have the care of a water-cooled turbo-generator such as the author suggests, without the insulated windings being in some way entirely covered with a damp- and water-resisting material like lead—which of course would not do—or some material to prevent any escape of water permeating the insulation. In any case the water-cooling units should be set so far away from any of the windings that a short-circuit between phases, or from phase to earth, could not reach the cooling vessel and allow water thereby to drench the stator.

Mr. G. W. Partridge: The author appears to have been very unfortunate in his use of these machines, and it does not speak very well, as far as I can see, for the ingenuity of English contractors if the sort of faults to which he refers occur in present-day machines. I rather think that most of the faults of design have been taken in hand and considered by English contractors, and that the designs of the machines have been considerably modified to meet them. With reference to the author's remarks on page 126 regarding the solid rotor, I think I am right in saying that to-day the solid rotor is nearly always used for small machines and for machines running at 3,000 r.p.m. up to about 12,000 kw., in which case the diameter will be about 33 inches; but, beyond that size, contractors to-day are using a plated construction for their larger rotors to satisfy the requirements for safety, so that it is possible to get inside the material more and be absolutely sure what is going on, which is always a difficulty in the solid rotor. I am rather surprised to find that the author has attacked the Parsons flexible coupling. He mentions that it has been done away with on the Continent. I have seen a great many contractors on the Continent, and I was recently talking this matter over with a contractor who has made about 5 million h.p. of turbines and from 2 million to 3 million h.p. of turbo-generators. He told me that the flexible coupling was one of the best things that Parsons ever did for the turbo-alternator. It is quite true that the Germans such as the A.E.G. and Siemens have discarded the flexible coupling, but this has been to save expense, and if I were ordering a large machine I should prefer a flexible coupling. Amongst the numerous faults which the author has referred to, he has omitted to mention one very serious trouble which has exercised the minds of contractors a great deal, namely, the sustained or even momentary single-phase short-circuit. The effect of such a short-circuit is to burn the ends of the rotor keys and wedges, and very often disturbs the windings themselves and the end connections of the machine, expecially if they are not properly bonded together. As regards the reliability of the turbo-generator, I have had experience of between 30,000 and 40,000 kw. of such machines, and I think I have got the most severe service in this country; we often have short-circuits, sometimes as many as 20 or 30 a week. Up to the present, however, we have been very free from the faults and troubles referred to by the author. I am rather surprised that he advocates steel-wire clamping at the end of the rotor. Apart from the difficulty of getting even tension on the material, it is not always desirable to make use of only one metal. With regard to the author's design of water-cooled turbo-generator, it seems to me that, first, this would add considerably to the expense of the machine, and, secondly, there would be difficulty due to blocking up of the channels by deposits. Some of the ducts are very small and are liable to become choked. I have had trouble in this connection with large transformers and we have had to clean the cooling coils by means of hydrochloric acid. In the third place, there is the difficulty of keeping the joints watertight. Some of these coils in certain positions of the machine after a few short-circuits, or stray field effect, would become loose and would rattle. In the fourth place there is the trouble of condensation. I am of opinion that, if the machine were not kept on constant load, condensation could never be entirely prevented. The water ducts also take up valuable space, and it is difficult to avoid large masses of magnetic metal in places where they are least desirable.

Mr. A. M. Taylor: I assume it is agreed to be vital and of increasing importance that alternators should be absolutely reliable under all conditions. The alternator makers are, of course, bound in their own interests to defend themselves against any charge of unreliability, and they would probably be content if it could be shown that only one alternator in five broke down within, say, three years of purchase. I know, however, of at least one case where, with the very best modern alternators, even half this reliability was not attained. I submit that if locomotives on main-line railways had only this degree of reliability nobody would care to travel. I presume that in that case the figure of reliability is something like 100 times as great. Assuming reliability to be so vital, I venture to suggest that since we are to have in the near future stations generating at 30,000 to 60,000 volts, which will necessitate step-up transformers, it is a question whether the transformers could not be efficiently used to improve the reliability of the generators. Suppose, for example, that instead of earthing one end of each generator coil the coil were insulated at both ends and the two ends taken out to a corresponding coil on the primary of the transformer, and that the mid-point of this coil were earthed, we should then at once halve the potential stresses between any part of the generator winding and earth. The arrangement would really be the equivalent of six phases on the generator, though there would be only three coils as at present. Suppose, further, that a second set of three coils of intermediate phase were added to the generator, then for the same kilowatts the voltage of all six coils could be again halved, thus reducing to one-quarter the stresses to earth. The second three coils would be connected to a second lot of primaries on a second transformer; and in order to rectify for the phase displacement, the second transformer

would have its high-tension side connected in delta, while that of the first transformer would be in star, both being coupled to the same busbars. Besides reducing to one-fourth the stress to earth on the generator winding, the arrangement would have the decided advantage of reducing the tendency of the sound coils on the generator to send current into the faulty coils, for, in the case of coils that are feeding into different transformers, there are two primary and two secondary reactances in series. I believe that when the great advantages of multiphase transmission are appreciated this (multiphase) form of transmission will be adopted for all long-distance work, and in such a case the six-phase double-star generator winding mentioned above could be connected direct to the cable or line, this at once giving 70 per cent better regulation on the cable system and 58 per cent of the line losses; or, conversely, greater distances could be covered for the same amount of copper. In cases where three existing cables run to an existing substation, approximately 70 per cent more power could be supplied through those cables by running them as a six-phase system. At the substation end an ordinary three-phase transformer could be used to give a three-phase supply. The special generator can be dispensed with if a transformer be introduced between the busbars and the line. A 12-phase long-distance transmission line could be carried out with two six-phase cables, and would reduce the line losses to 29 per cent of that of the three-phase system and improve the regulation 340 per cent; or, conversely, the distance of transmission could be extended $3\frac{1}{3}$ times for equal copper investment.

Mr. W. McClelland: I am particularly interested in the application of large turbo-generators for electric propulsion, and it seems to me that the author has not at all exaggerated the difficulties in connection with electric machinery for ships. We have heard from time to time that America has led the way in the matter of electric propulsion for naval ships. The conditions there in my opinion are different from those in this country. The coast line in America is many thousands of miles in length, whereas we have only a few hundred miles of coast line to patrol at cruising speeds in peace time, and the economies gained at cruising speed with electric propulsion are great. At the present time, so far as I can ascertain, we cannot gain any economy with electric propulsion at maximum speed of the ship. I believe it to be the fact that America has sacrificed a little at maximum speed in order to gain the economy at cruising speeds. For large naval ships very high powers are required, and to obtain maximum speed we must have plant of the highest possible efficiency. These very high powers, as the author tells us, mean very large air trunks if this method of cooling be adopted. Taking the case of the battle cruiser to which the author refers and which develops about 180,000 h.p., the air trunks for circulating air to the motors alone would have an area of something like 275 sq. ft. or, if taken as a circular trunk, about 19 ft. diameter. In addition to that, a slightly larger quantity of air has to be taken to the generators; but, the generators being fitted approximately amidships, the problem is not difficult. In order to gain economy with reduced length of shafting the main motors must be fitted as near to the propellers as possible; they must therefore be placed right aft. To run vertically in the after part of a ship an air trunk of 275 sq. ft. area, or the equivalent, would be impossible; it would foul the aft turrets; and if air trunks equivalent to that area were run horizontally it would tend to affect seriously the watertight sub-division of the ship. For this reason I am pleased that the author has raised the question of air circulation and water circulation. I do not know whether or not the author will justify his proposals with regard to his water-cooling system, but he certainly attempts to tackle the cooling difficulties of turbo-generators in connection with ship work at the source, and on this account I shall be very interested to hear further remarks from expert designers and manufacturers of large turbo-generator and motor plant.

Professor S. P. Smith: There is one point of view which the author of the paper does not seem to have taken sufficiently into account in the first part of the paper, where he deals with the troubles that operating engineers have experienced, but it is a very important one. We must not forget the way in which many machines are bought and sold in this country. I refer to those cases where the buyer does not go for the best, but for the cheapest machine. One cannot have too much sympathy for those who buy merely for cheapness. If they get trouble they have to pay to get out of it; and it may cost them, before they finish, more than they would have paid if they had bought one of the best machines. Obviously, if we demand that a machine which is admittedly difficult both to design and to build be given a factor of safety lower than that in other classes of machinery, we must expect trouble. Add now to this evil of cutting prices the fact that the machine is continuously worked at its utmost capacity through lack of spare plant, and one is less surprised than ever that troubles arise. But to my mind there is not very much argument in the first part of the paper. The fact is that there are many very good turbo-generators of large output which have been working for years without giving any trouble at all. Further, many of the troubles mentioned are almost out of date, and although there may be machines which give trouble, most manufacturers have learned the remedy long ago. For instance, the author deals with slack cores. True, there may be makers who do not trouble much about core building, but surely we ought not to be told in the year 1920 how to build cores. If proper care be taken to punch the plates properly, to remove all burrs and to fit and secure the keys, we can make a very solid construction where the losses will be very low indeed and no trouble with teeth, etc., will be experienced. I merely give that as an instance of a lot of the criticism which I find in the first part of the paper. With regard to the method of cooling, one must not be misled by the fact that water cools so much better than air. Granted that water is a much better cooling medium, yet it must be borne in mind that the temperature of a winding does not depend entirely on the cooling medium; it depends largely on the insulation, as the author has appreciated in his paper. Thus, while the iron of the rotor or the stator may be very cool indeed, the winding

may be quite hot, simply because the heat cannot flow through the thick mica insulation without a considerable temperature gradient. Therefore we cannot always get a machine to be as cool as we should like it to be. There is no time to go fully into the water-cooling proposal. It needs very critical examination. There may be good points about it, but I do not think it would be a success as proposed. The remark I should like to make in conclusion is this: we must remember that we can build good machines. Good machines have been built in the past and no doubt will be built in the future; but we must remember that there will always be the necessity of having a sufficient margin of safety; particularly in large machines, where we do not know entirely the conditions inside the machine, we must not cut matters too fine—soundness is more important than cheapness.

Mr. F. H. Clough: In the early part of the paper the author describes the large number of faults in design of turbo-alternators which have led to failures of machines. Time will not allow me to comment on the various faults in construction which he describes, but I think I may say in general that many of these faults are much out of date and, further, some of them have never been committed at all by the leading makers of this type of machinery in this country. He next suggests improvements in design and accentuates the necessity of keeping low temperatures so as to avoid destroying the insulation, and of very securely holding the stator bars in place so as to avoid displacement under short-circuit. I agree with the necessity of avoiding high temperatures which may in any way impair the reliability of the machine, but I do not think it would be possible to avoid such temperatures if heavy solid stators bars are used such as he suggests, and in general I think it is preferable to reduce the forces which cause distortion of the windings rather than attempt to design windings which will withstand excessive forces. With regard to the author's suggestion for using water cooling on stators, I am afraid that the design which he describes would not be a feasible one, as it would introduce difficulties and risks which do not exist at present, and the reliability would be poorer than that of machines which we now have. I am inclined to think that the modern turbo-alternator meets present-day operating conditions much better than the author leads us to believe, and the failures which occur are not nearly so frequent as he states. Finally, I should like to say that I think this paper is a very desirable one, as it tends to open an interchange of views between the operating and designing engineers, and such a discussion will certainly lead to progress in the design of machines.

[The author's reply will be found on page 148.]

South Midland Centre, at Birmingham, 28 January, 1920.

Mr. W. Wilson: To my mind the author has shown the advantages of liquid cooling the most thoroughly in the case of electrical propulsion for marine purposes. The American Navy have recently been conducting experiments in marine propulsion, which have culminated in the equipping of their latest battleships in this way. It would be interesting to know whether they have adopted liquid cooling in these cases and, if so, how they have solved the problem.

Mr. W. M. Cranston: The author proposes to dispense entirely with the present system of air cooling and to substitute for it a system of water ducts. If we take 15 degrees C. as the approximate difference in temperature required between the iron surface and the air in the duct and assume the corresponding difference in the case of water cooling to be negligible, we can permit an additional internal temperature rise of 15 degrees C. Taking 50 degrees C. to be the present temperature rise from all sources, we can thus allow 40 per cent greater loss provided other factors remain constant. Unfortunately this is not so, since we rely on the cooling from the air-gap surfaces of both stator and rotor as a valuable heat path. The efficiency of this path depends entirely upon the rate of change of the air in the gap, and in the author's ideal machine this heat path would disappear. The importance of this will be evident when I say that in a machine having a stator loss of 200 kw. something like 60 kw. would be dissipated from the gap surface of the stator and a similar amount from the rotor. In the absence of air ventilation the whole of that heat would have to be conducted across the stampings at the point of highest loss and I am afraid this would practically absorb the whole of the 15 degrees C. gained. Whatever may be the future of water cooling as an auxiliary, I think the main cooling medium will continue to be air. It may be that we shall use a closed circuit with some form of cooling device. Then we shall have absolute cleanliness and it will be possible to remove the oxygen from the air before admitting the latter to the machine, thus eliminating the fire risk of which the author makes so much. A gas has the great advantage over a liquid, that the heat in it can be extracted mechanically even though the gas is at a lower temperature than its surroundings. This opens up great possibilities of using the turbo losses to some advantage.

Mr. R. G. Jakeman: I think the author has been rather unfair in regard to the present designs of turbo-alternators. It would be very instructive if another appendix could be added to the paper giving the number of breakdowns of this class of machinery for the past five or six years, together with the total number of machines in operation. In his calculations for liquid cooling, the author appears to have assumed that all the channels provided are completely filled with the liquid. Referring to the narrow slot shown in Fig. 8 (*f*), it seems quite likely, however, that the centrifugal force would cause the liquid to be flung outwards, leaving a vacuum at the bottom of the slot. This would reduce the surface of liquid available for cooling, and, although the velocity would be increased, the advantage of this particular shape of duct would be considerably less than might be expected.

Mr. F. Forrest: The present method of cooling

large turbo-alternators by blowing through them large volumes of air cannot be regarded as satisfactory, especially when one bears in mind that the cooling air may be saturated with moisture and may carry, as it usually does, a considerable amount of dirt. I believe future development will tend towards some system of liquid cooling which will be much more effective than the present crude method and free from its obvious defects. There are grave risks in adopting water cooling for the stator of a high-voltage alternator, and I do not believe that this will ever become standard practice. Forced oil cooling for both stator and rotor would be a satisfactory solution of the difficulty, although the volume of the cooling ducts for the oil, compared with those necessary for water cooling, would be about $2\frac{1}{4}$ times as large. The specific heat of transformer oil is about 0·55, whilst its specific gravity is about 0·85. The oil can be circulated by means of a pump driven from the turbine shaft (in the same way as the lubricating oil is now delivered), and after passing through the machine could be cooled in a separate cooler. The cooling of the turbo-generator would then be done in a similar manner to the latest method of cooling large transformers, in which the oil is forced through the windings by means of a pump and the hot oil cooled in an external cooler.

Mr. R. Orsettich : A paper discussing the failures of turbo-generators is bound to be to some extent historical, and, considering the rapid and continuous development of this type of machinery, a number of the points discussed are likely to be somewhat out of date, so that not all the improvements suggested in the paper are necessarily new or acceptable. This is particularly the case, as under present conditions a long period, sometimes two or three years, elapses between the moment when the plant is ordered and the time when it is taken into beneficial use. The author has some doubt as to the advisability of running turbo rotors at high speeds, owing to the high stresses which take place in the various parts. Whilst this is no doubt the case, it must be pointed out that the example selected, viz. a 36-in. diameter rotor running at 3,000 r.p.m , is at the present moment the extreme case, as it corresponds to an output of something like 15,000 kw., and to my knowledge no machine of this size has yet been built in this country. On the other hand, the progress of the steel makers has been such that that industry has no difficulty in supplying materials which amply fulfil the requirements of the electrical manufacturers, so that one can easily guarantee at overspeed a factor of safety of not less than 3 between the running stresses and the elastic limit of the material. The troubles mentioned in connection with the stampings of the stator are acknowledged by manufacturers to have taken place in connection with generators with split stators, and although such split stators are made and can be made to-day, the common opinion is that they should be avoided whenever possible, and that it is preferable to build and wind the complete machine on site rather then employ a split stator. The failure of the keys is due to defective workmanship rather than design, and no doubt is to-day not recurring. Similarly, inaccurate punchings are not found in any up-to-date manufacture, especially in view of the efforts of the designers to reduce the already far from light iron losses of this type of machine. Paper insulation is not used on these machines by the majority of makers, as paper is well known to be unable to stand high temperatures without charring, and because it can easily be replaced by the use of either enamels or mineral insulators. Mica and micanite are to-day the only satisfactory insulating materials available for the windings, and are the only materials which can stand high temperatures without burning or becoming spoilt. The author's objections to paper are well founded, but this disadvantage can be greatly reduced by specifying the percentage of paper in the micanite to be not more than 15 or 20 per cent. With large outputs windings made with stiff bars are not advisable on account of the very heavy eddy-current losses. A large section of solid copper is in the end extremely wasteful, as the central portion cannot be loaded up equally with the remaining, so that solid bars imply indirectly a bad space factor, and therefore a wasteful and poor machine. If possible, manufacturers would much prefer to use solid bars, as they are fully aware of the advantages of solid conductors. Soldered connections for portions of the winding which are covered up should be strongly objected to, although the author mentions that they are generally adopted. There is always a danger that the enclosed portion of a coil may reach a high temperature, which would cause the solder to run and bring about a short-circuit between adjacent turns. For this reason only brazed joints are used for enclosed windings, both for the stator and for the rotor. The author mentions the use of coil supports for the rotor, consisting of metal packings between the loops. The latest practice in rotor construction does not require any supporting of the loops, as it is found that with well-shaped coils there is no tendency for the turns to slide over one another and bring about the collapse of the coil under the influence of centrifugal force. Furthermore, in the construction of the rotor only fireproof material is now employed, such as pure mica between the turns, asbestos or bakelite blocks to support the mica tubes, and micanite to insulate the coils from the caps. The author mentions permanent connections between the cables and the stator winding ; against this it should be pointed out that most specifications definitely ask for terminals, and that there is no difficulty in supplying a safe type of terminal in which the connections are made by means of mechanical clamping of the cable ends with the winding ends, without any intervening insulating material. In large machines it is always advisable to carry these mechanical clamps on two insulators each, to avoid any danger from the failure of one of the insulators. With reference to the question of dampers, present practice is always to install at least one damper in the duct of the incoming air, and it is also advisable to install another one at the outlet. Apart from the necessity of operating these dampers in case of an accident, which may cause fire, either in the filter or in the machine, such dampers are necessary to shut off the air when the generators are standing during week-ends and when a large accumulation of damp could take place. It is also strongly advisable

to keep the dampers shut on starting up until the generator becomes thoroughly warm, especially during foggy weather and when the temperature of the incoming air is likely to be higher than that of the machine at rest. The author mentions the large number of turbo breakdowns in French stations. In my opinion these are due not so much to any inherent fault of the windings themselves, as to the fact that in France a large number of generators are installed for pressures between 11,000 and 15,000 volts. These voltages are in themselves far too high for practical working on any machine, and particularly on turbo-generators, where the restricted space and the clamping necessary for the coils increase the probabilities of damage due to the brush discharge which takes place when the machine is at work. Whilst no doubt such machines can be made, their installation is a doubtful commercial proposition. With regard to the author's proposals regarding generators fitted with liquid cooling, I have no doubt that sooner or later such a plan will have to be adopted if the outputs of generators are still to be increased. There are two remarks, however, which I should like to make in connection with the designs put forward. The first is that I do not think it advisable to use long bolts passing right through the stator stampings, even if such bolts are made of non-magnetic material, because they would heat up in any case to such an extent that they would not be of much use as tie rods. The second is that in a stator or rotor winding which is clamped on both sides as shown, there would be less flexibility and more tendency to distortion under the expansion due to heating than in the average type of machine as made to-day.

Mr. H. W. Taylor: The discussion on this paper will, I think, tend to a better mutual appreciation of the difficulties manufacturers and users separately experience, either in making or in operating turbo-alternator plant. That their points of view are different will be appreciated by recalling that the author in various parts of the paper seems to suggest that improvements, for instance in cooling the machine, enable a rotor of smaller diameter and, therefore, also with smaller centrifugal stresses, to be built. The designer's point of view is that any improvement in the physical properties of the materials he deals with, or any improvement in the system of constructing the machine, helps to use the material to better advantage than before and so obtain a larger output from the same size of machine. The author's reference to centrifugal stresses on page 126 also calls for comment. The designer's point of view is that centrifugal stresses are proportional not necessarily to the speed in revolutions, but to the peripheral speed, and that the difficulty in designing 3,000-r.p.m. machines is that with the same peripheral speed a smaller diameter results at the higher speed of revolution, and that from geometrical considerations a less quantity of copper, or in other words a less armature-reaction loading, can be used per unit length of periphery. In the first portion of the paper the author cites a number of mechanical and electrical defects which may occur in turbo-alternators, but I think the fact that these possible defects are known should enhance rather than detract from the present general scheme of construction, for the reason that these defects should not recur if the whole of past experience in manufacture and design is brought to bear upon current work. The recurrence of the same defects in the same make of machine is often due to lack of organization in the factories which have constructed them. In some places the electrical and mechanical designs are relegated to separate departments, and these again are sharply divided from the works organization where the machines are actually constructed. I think also it is a mistake to have the turbo-alternators built in the same factory or section of the factory, and the work on them directed by the same people who are associated with smaller machines. With smaller machines the question of cheapness and quickness of production is paramount, while with large machines such as turbo-alternators such considerations are fatal to the quality of the resulting product. On page 129 the author describes a method of constructing and connecting laminated bars which one would gather is new. His description, however, covers a method of dealing with eddy currents in stator windings which was first adopted by the British Thomson-Houston Company over 8 years ago. The patent describing this method in the original instance is not mentioned* in the Appendix; it is 10919/13. With reference to the question of short-circuits, it has often been thought necessary to have the stator end windings very securely held in place by massive clamps.. There are two methods by which short-circuit difficulties may be overcome. The first is, as already mentioned, by severely clamping the windings so as to prevent any movement when the stresses occur, and the second is so to design the windings that heavy stresses do not come into existence, even under the most severe short-circuit. The form of two-layer basket winding, which has been in exclusive use on turbo-alternators built by the British Thomson-Houston Company, is constructed on the second principle. An outer insulated ring supports the coils, but no clamps are required to retain them in position under stress of service. The latter part of the paper is devoted to some suggestions for cooling machines by circulating liquids. The suggestion to use water as a cooling medium is of course not new, and I believe that, in future, rotors will be partly cooled, not, however, by water but by oil, a portion of which will be deflected from the main lubricating system and if necessary cooled to a rather lower temperature than is necessary for lubrication. Also I believe that the stator will be relieved of a certain amount of its heat by the same medium. With regard, however, to the novel portions of the author's suggestions as indicated in Figs. 8 (*f*), 10 and 11, I do not think they will appeal to designing engineers, at any rate in their present form. There are two methods of attacking the problem of designing a cool machine. One is to improve the cooling arrangements as the author proposes, and the other is to design the machine so that it will generate less heat. In my opinion the first method should be accommodated to the second, and not the second to the first, or, in other words,

* Since added.

the methods shown in Figs. 8 (*b*), (*c*), (*e*) and (*f*) are bad because the cooling arrangements occupy space which might be more usefully occupied by magnetically or electrically active materials. In fact, I think it is axiomatic that only such materials, apart from the necessary amount of insulation on the rotor coils, should be used in the active belt. With regard to Figs. 10 and 11, Fig. A herewith is of interest in showing that the amount of copper required to give modern outputs is about 4 times that indicated by the author, and he must therefore reconsider the arrangement of his end windings and proposals for cooling them, to allow for this fact. Furthermore, the author has anticipated that eddy currents will be introduced in his metal clamps, but has, I think, erroneously supposed that by using material with a high specific resistance

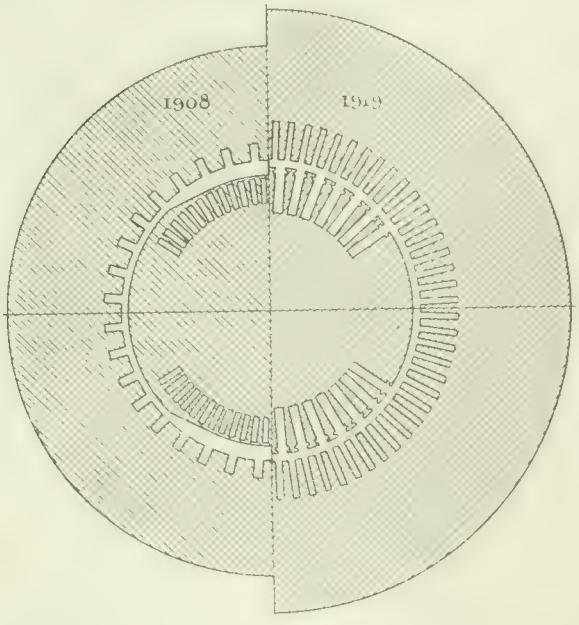


FIG. A.—Punchings used by the British Thomson-Houston Company in 1908 and 1919 for the same stator-face diameter, showing the growth in width of the active belt.

the losses will be reduced. As a matter of fact they will probably be increased with increased specific resistance, as the mutual currents in the metal clamps will be very much like the secondary currents in a current transformer, which, as is well known, are constant over a large range of resistance.

Dr. M. Kahn : To use liquids as the cooling medium for turbo-alternators, as advocated by the author, appears to offer a number of advantages. It is, however doubtful whether a water-cooled generator would run substantially cooler than an air-cooled machine. The cooling water entering the machine must not be colder than the temperature of the air in the engine room in order to avoid condensation of the moisture of the air, when coming in contact with the cooling-water ducts of the generator. The temperature rise of the windings of the generator above the initial temperature of the cooling water will be practically the same as the temperature rise of air-cooled machines, as the temperature gradient between the windings in the slot and the cooled surfaces is independent of the cooling medium. Average values of this gradient are 40 degrees F. between conductors and core, and 40 degrees F. between teeth and cooling medium. Allowing for a temperature rise of the cooling water of 15 degrees F. as mentioned in the paper, we arrive at a total temperature rise of the copper in the slots of large turbo-alternators of 95 degrees F. With an engine-room temperature of 80 degrees F., limiting the temperature of the cooling water to this figure, the temperature of the hottest point of the alternator is 175° F. In large turbo-alternators mica insulation is now generally employed as the insulation of the windings in the slots, and the temperature just mentioned is well below the temperature of 250° F. which is given in Fig. 7, Curve B, for 20 years' life of mica insulation To reduce the temperature still further to 150° F. as advocated in the paper would be difficult on large turbo-alternators whatever cooling medium were used, and would necessitate a considerable increase in the dimensions of the machines. As an increase in the diameter or length of high-speed machines of large outputs tends to decrease the mechanical safety factors, the machine with the lower temperature rise may well be less reliable.

Mr. J. Shepherd (*in reply, communicated*) : As the discussions at the various Centres have generally run in parallel lines it will save much repetition if my reply be classified under salient heads. In addition, specific points not sufficiently dealt with in this manner will be further replied to when considering the remarks of individual speakers.

Reliability of present designs.—Generally the various designers consider my recital of breakdowns to be painted too darkly and that modern machines at any rate are not subject to the failures stated. In hardly any case has the discussion been definite and the speakers have not particularized the class of breakdown which they say has been exaggerated. The inference to be drawn is that the necessity for any change in design has not been established. With the sole exception of side slip of rotor end loops, I have seen or had experience of all the breakdowns noted. They have not all taken place in the same station or with the same maker's plant. For obvious reasons I cannot particularize the stations involved, nor the makers whose plant has failed. Failures are more or less common to all countries and all manufacturers. The following are a few examples of failures dealt with by various authorities :—

British.—See Mr. Seaton's remarks, *Journal I.E.E.*, 1916, vol. 54, p. 179.

American.—See " Fire Hazards in Turbo-alternators," Report by Technical Officials of U.S.A. Fire Insurance Offices.

German.—See technical Press for breakdowns in electric stations on the Rand.

Continental.—See report of Committee of French Users of Turbo-alternators, *Electrical Review*, 18th April, 1919.

The danger of side slip of rotor loops was dealt with

at some length by Dr. S. F. Barclay, *Journal I.E.E.*, 1918, vol. 56, p. 472.

Other speakers have argued that whilst earlier machines may have given some trouble, later designs have materially improved. This statement is undoubtedly true, but the size of the electrical systems to which the units are attached has increased also, and the shocks, stresses and risks have very much increased likewise.

Necessity for change of design.—As single generating units increase to upwards of 50,000 h.p. it is not always remembered that the driving torque must of necessity be transmitted through the insulation surrounding the stator conductors. Further, the bars must be very thoroughly laminated and, in effect, the component parts are held together by the insulation surrounding them. We thus have a mechanically weak stator bar held together by a mechanically weak insulation subjected to all the driving torque of the steam turbine and to the highly impulsive stresses on short-circuits. The choice of insulating material is very limited, and all of it is unsatisfactory mechanically. The obvious remedy, viz. to use more insulation, is not feasible owing to temperature considerations. The only solution hitherto adopted is the insertion of inductance and the more frequent use of supports or clamps on the stator end-coils. As the speeds of machines increase, the output per cubic inch of material increases and the loss also, requiring more heat to be dissipated and resulting in the limiting capacity of air ventilation being approached, especially in the rotors. We thus have two limiting factors, mechanical weaknesses of stator bars and difficulty of cooling by air; consequently a change of present designs must take place sooner or later. By adopting liquid cooling the continuous winding slot becomes possible of consideration, as it combines the maximum of cooling effect and the minimum of stress upon the stator winding and its insulation. Of course the close proximity of water-cooling devices to the high-tension windings is a proposal that naturally does not appeal to one unless the compensating advantages are considerable. These are: (1) Low resistance and numerous heat paths. (2) Continuous winding supports of a mechanical character. (3) Absence of air circulation and of fire risk. The disadvantages are: (4) Risk of water leakage. (5) Risk of water condensation. (6) Insulation difficulties. (7) Eddy-current loss in the coil supports. The advantages described have been set out in the paper and need not be discussed further. The anticipated risk of water leakage is likely to remain until actual construction shows that it is negligible. Condensation difficulties are discussed in the paper; machines have been running some considerable time with water-cooled rotors, the water inlet temperatures being 65° to 70° F., without condensation difficulties. Insulation difficulties are not serious; it will be necessary to insulate the end turns as stoutly as the straight bar within the stator slot. Where the under and upper bars meet and are connected together specially good insulation will be required, with adequately long leakage surfaces. In air-cooled machines the presence of dust carried into the stator and deposited upon the windings necessitates a leakage surface of some considerable length. With water-cooled machines the case is different; little or no dust should be deposited on the windings. The cooling devices provide the means of using other kinds of covering. After the ordinary mica and tape insulation has been wrapped on, an external taping of vulcanizing material could be cured in place by passing low-pressure steam through the coolers, this material being used as a seal and not *as insulation.* Eddy-current losses are negligible so long as no magnetic material is employed in the construction of the supports.

Practicability of water cooling.—Several designers have stated that the designs suggested are not practicable, but they omit to say in what particular feature. It will therefore be necessary to review briefly each novel feature proposed.

Rotor coolers.—As an example is generally better than argument, I should like to say that Messrs. C. A. Parsons and Co. have constructed several machines the rotors of which are entirely water cooled. The machines are of considerable size, 10,000 k.v.a. at 2,400 r.p.m., the cooling construction closely following that shown in British Patent No. 16986/1914. A self-contained circulating system is employed with a temperature rise of cooling water of 15 to 20 degrees F. The modifications necessary to the rotor construction to include the coil supports need raise no misgivings; every constructional feature proposed has been in extensive use for years in other branches of engineering.

Rotor bands of steel tape.—The construction suggested is free from the defects of the old type of steel-wire bands. The bands can be wound on with any initial tension desired and are centred independently of the rotor coils. Both ends of the tape can be mechanically anchored solidly to the metal of the rotor coil support. From the nature of the stator construction proposed and shown in Fig. 10 no arc on the stator winding could reach the rotor band.

Stator core coolers.—Those proposed are of simple plate construction to enable sound and easily fusion-welded joints to be made. Those members who have experience with similar joints will require no further assurance, and to those who are not familiar with such joints I would suggest that they take an early opportunity of inspecting fusion-welded or seam (spot) welded joints; the work will then speak for itself. Before building in place each cooler could be subjected to a testing pressure of over 10 times the working pressure.

Stator end-coil supports.—The particular design shown in the paper is in the form of a conical ring on which the bottom layer of windings is laid and between them driving projections are bolted forming the winding slots. Similar conical rings were used by Swiss designers 10 years ago, but were abandoned owing to ventilating difficulties. To give the most adequate cooling the coil supports must be provided with hollow water channels. Those shown in the paper are the most suitable from the cooling standpoint. Modification with water ways formed of solid drawn pipes coiled up and embedded in the cooler could be suggested to those who dislike welded joints. The external clamp is of similar construction and calls for no further

comment. The novelty in both the support and the clamp is the provision of winding slots and water cooling, and the only legitimate criticism is that of possible water leakage. With a wide experience of engineering in many branches I must disagree with the various speakers who contemplate difficulty in constructing sound joints for so moderate an internal pressure. In Staffordshire thousands of tons of welded steel piping are constructed monthly for much higher pressures and under more primitive conditions than those of the workshops where electrical plant is constructed. The pipe makers certainly have the courage of their convictions.

Fusion welding.—This is suggested for constructing various parts of the cooling devices and it may not be out of place to say something of the uses to which it has been adapted. Roughly there are three types of fusion welding: (*a*) oxy-acetylene, (*b*) the electric arc with metallic electrodes, (*c*) spot welding. (*a*) Oxy-acetylene welding is daily used in the construction of high-pressure and high superheat pipes for welding on flanges, bosses and tees; for the construction of oil tanks for oil-cooled transformers; for the construction of steel bottles for high-pressure gases up to 5,000 lb. per square inch. The joints of pipework for upwards of 750° F. offer considerable difficulty, as no known packing between the flanges is suitable. Consequently, steam joints have been proposed and will shortly be on the market, constructed as shown in Fig. B herewith, with fusion-welded joints, the joint

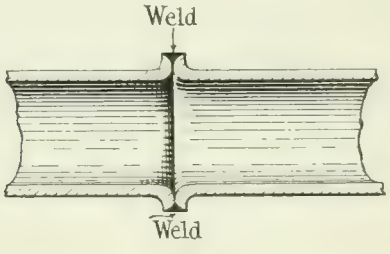


FIG. B.

being reinforced by bolts fixed in loose flanges made in halves and pressing against the turned-up pipe flanges. The full steam pressure will be exerted upon the welded joints, which must be welded *in situ*.

(*b*) Arc welding is in daily use for boiler construction for working pressures of 200 lb. per square inch, and electrically-welded seams may shortly supersede riveted joints. (*c*) Ten years ago Dr Ferranti was exhaustively investigating the designs of steam turbines suitable for high pressures and for superheats approaching 1,000 degrees F. He decided to attach the blading to the rotor drum by spot welding as the most reliable of all known methods. These few examples are applications of fusion welding to meet much more arduous conditions of working than any suggested by the author. He entirely dissents from the ideas expressed that the successful application of fusion welding is beyond the capabilities of electrical workshops.

Oil versus water cooling. Doubt regarding the soundness of the joints has caused various speakers to suggest oil in place of water cooling. There are advantages and disadvantages with both media. No construction of joints which cannot be entirely relied upon should be allowed with either oil or water. The possibility of leakage during a burn-out must be considered, and under such conditions oil would appear to be more risky than water. The risk of obstruction of the passages by oil sludging must also be considered. The construction of coolers shown in the paper would suit either oil or water if a closed cooling system were provided.

Dealing now with the remarks of individual speakers, Mr. Field is the only designer at the discussion in London who considered there are grounds for a recital of breakdowns, and consequently room for improvement. I am much indebted to Mr. Field for the fair way he has considered my paper. The proposal of re-circulated air through an external cooler only gets rid of the difficulty of treating the air itself, but it leaves the alternator with its present defects. The difficulties of insulating the curved portion of the stator windings I have already dealt with. If the air be got rid of, and a group of the mica-insulated bars be impregnated together in a water-tight compound, surface leakage could be avoided; the problem is no worse than that of a high-tension three-core cable joint. Whilst I am sure that changes in design will constantly occur, we are always likely to have the difficulties of heat dissipation and mechanical overstressing of insulation, the two features fully dealt with in the paper. If I understand Mr. Field correctly, it does not materially matter of what metal the end stator supports (adjacent to the live conductors) are constructed, as any loss in the supports is gained by reduction of the corresponding loss in the stator bars. This is a matter of some importance as it widens the choice of suitable materials. I note with much interest that Mr. Field is of opinion that air cooling must ultimately give place to liquid cooling.

I am sorry that Mr. Dickinson has some difficulty in understanding the point of my paper; I think the title clearly sets out my idea in writing the paper. I note that Mr. Dickinson agrees with the statements respecting the failures of turbo-generators but not with the remedies proposed. I have dealt with this matter in my opening remarks on the discussion. Under modern conditions of operating a large supply system a bad burn-out may occur on any machine. At present the machine is stopped as soon as possible and, if still on fire, the hose pipe is then employed; whereas with water cooling a bad burn-out would set the water at work almost instantly and at the very seat of the flames. Afterwards the cooling elements give an easy means of drying out, by passing hot water or steam through them. When liquid cooling is developed, electrically-operated valves will form part of the outfit, and will be connected to the protection relay system and equipped with suitable time-limit devices.

In reply to Mr. Partridge, I have already pointed out that the failures outlined took place in several stations and with both British and foreign plant. No attack was made on Parsons flexible coupling; mention was, however, made of difficulties experienced with a type of coupling and, generally speaking, solid couplings are

taking their place. For high-speed machines I consider a steel tape to be the safest kind of band under the conditions set out. I am aware of the magnetic requirements of a bronze ring next the polar faces, and this is provided for and shown in Fig. 9. Whilst with a solid band the tensions are not under control, with a flexible band the tensions may be adjusted to any desired amount.

In reply to Mr. A. M. Taylor, I think a reliable alternator should run for 10 years without a breakdown, neglecting of course the usual overhauls and small replacements. His contention that one machine in every five may break down is quite a modest requirement.

Mr. McClelland restricts his remarks to the marine propulsion side, and I am pleased to have his approval of my statement regarding sea conditions. As Electrical Director at the British Admiralty his experience carries great weight. Personally I feel sure that before marine propulsion on a large scale is solved machines will be required of the types outlined in the paper. The driving torque of 180,000 h.p. through faces of insulation under sea conditions is not a small problem nor one solved by the use of electrical plant as now constructed.

Professor S. P. Smith attributes the breakdowns to the purchase of cheap machines; by doing so he practically classes the majority of British and Continental machines as cheap, meaning thereby not cheap in the ordinary accepted sense of the word, but as being something poor and inferior. I am sorry I cannot accept his suggestion. I have considerable experience in buying machines and I cannot recall a single instance where inferior material was introduced into turbo-alternators to effect a saving in constructional cost. At the same time I thoroughly agree with the concluding sentence of his remarks.

Mr. Clough states that some of the faults have never been committed at all by the leading makers of this type of machinery in this country. During the discussion I pressed Mr. Clough, but without success, to specify what faults had not been committed as stated, and as I have dealt with the matter in my opening remarks there is nothing further which can be usefully said. I do not suggest the use of heavy solid bars; on the contrary, one must recognize the necessity of laminated stator bars and consequently the necessity of providing more perfect support to them. As Mr. Clough does not specify the difficulties he anticipates through stator water cooling, I can only refer once more to my opening remarks.

Birmingham Meeting.

Mr. Wilson raises certain questions regarding the method of cooling electrical plant used in the United States Navy. From accounts in the Press (*General Electric Review*, April 1919, and *Journal of the American Institute of Electrical Engineers*, January 1920) air cooling is used in the U.S.S. "New Mexico" and U.S.S. "Tennessee." The following statement occurs in the American *Journal*: "The machines are of the usual construction except that special provisions have been made to avoid salt deposits in the windings. This is a trouble which is likely to occur where machines are operated in salt-laden air." No details have been published respecting the method of eliminating salt spray or salt. Steam coils are apparently provided inside the generator framing to prevent surface condensation.

Mr. Cranston argues that there can be little gain in cooling effect with water against air. That is not the experience with rotor cooling nor is it a generally accepted opinion.

Mr. Jakeman states that the rotor ducts will probably be only partially full of water. That of course is only a surmise; even if only half full there would still be a gain of over 40 times the cooling effect of air.

As a user of turbo-alternators Mr. Forrest considers the present method of air cooling to be crude and unsatisfactory—my own opinion. The alternative methods of water and oil cooling I have dealt with already.

Mr. Orsettisch raises the question of maximum output of machines running at 3,000 r.p.m. I do not know the largest made in this country. Swiss makers say they are prepared to build machines of 20,000 k.v.a. at 3,000 r.p.m. I think most users will be surprised to learn that "paper insulation is not now used (on stator stampings) as paper is well known to be unable to stand high temperatures without charring"—a startling commentary on modern design. It would appear without further argument that more efficient cooling methods are already desirable, and further emphasis is added by the precautions Mr. Orsettisch considers necessary when using air for cooling. I quite agree that clamping bolts through the core of a stator are not desirable; for very deep cores, radially, bolts may be a necessity and are used freely by two experienced makers. With respect to thermal expansion, the increment in copper length to surrounding iron increment is rarely more than 0·05 inch, which is easily adjustable in the slack space at the ends of the core. I note with interest that so experienced a designer as Mr. Orsettisch is of the opinion that liquid cooling will have to be adopted ultimately.

Mr. H. W. Taylor correctly states that a designer and a user of plant view matters from different standpoints; their interests are, however, identical—the perfect machine. The first portion of my paper is not devoted to faults which *may* occur but to faults which *have* frequently occurred, with the exception of side slip. I am obliged for the particulars of the B.T.H. patent for stator bars and will include it with the others quoted. Regarding the attachment of stator conductors, I am acquainted with the method used by Mr. Taylor's firm, viz. loose separators and binding the conductors to their insulating rings by tape and cord, and I have no hesitation in stating that the continuous slot is the most mechanical of all possible methods of supporting stator conductors. With respect to rotor cooling we are really in agreement; the active material is so valuable that the minimum amount of it should be sacrificed to cooling ducts, and the method shown in Fig. 8 (*f*) combines the minimum sacrifice of *active* iron with the maximum of cooling (see table on page 133). With respect to the amount of stator copper shown in Figs. 10, 11 and 12, these diagrams are not scale drawings. Whilst they may not represent

the correct amount of copper according to Rugby practice, they are approximately correct according to designs elsewhere; at the same time with liquid cooling a re-proportioning of copper and iron would probably be necessary. Regarding eddy-current losses in the coil supports shown in Fig. 12, provided no magnetic metal is used the losses are so small that it is immaterial of what metal the supporting plate be constructed; questions of price and easy working will probably determine what metal shall be used.

Dr. M. Kahn raises certain comparisons between liquid and air cooling. I should anticipate figures of the following character with cooled condensate as the cooling medium:—

	Air	Water
Temperature gradient stator insulation	60°	60°
Temperature gradient cooling medium to cores	60°	20°
Temperature of cooling medium at outlet	110°	80°
Maximum temperature of copper	230° F.	160° F.

With regard to the curves in Fig. 7, these must be read as a general indication of results and not as absolute quantitative facts. Other matters besides temperatures are also involved, particularly the stiffness of the stator bars and the character of their supports.

THE HIGH-FREQUENCY RESISTANCE OF WIRES AND COILS.

By Professor G. W. O. Howe, D.Sc., Member.

(*Paper received 2 December, and read at a* Wireless Sectional Meeting of The Institution, 17 *December*, 1919.)

The last five years have seen a remarkable development in the application of high-frequency currents to telegraphy and telephony. In almost every such application, coils through which high-frequency currents flow form an essential part of the apparatus. In some cases they contain an ounce or less of the finest wire, in others many hundredweights of massive copper strip or tubing. In all cases, however, it is a matter of importance to be able to calculate or, at least, to predict the losses occurring in these coils when carrying high-frequency currents. Without this knowledge it is impossible for the designer to utilize his material and space to the best advantage.

No attempt is made to deal exhaustively with the subject in this paper. An explanation is given of the principles involved and it is shown how these principles can be applied to the calculation of the resistance of wires and coils. A method of measuring the resistance is described and the results obtained are compared with the calculated values. The use of multiply stranded insulated wire is discussed. In none of these matters, however, is the paper to be regarded as more than an opening contribution to a discussion on the subject.

It is now well known that the power transmitted by means of electric wires does not travel through the copper, but through the space between and around the conductors. The latter merely serve as guides whereby the energy is caused to flow along certain prescribed paths With free Hertzian waves in space there are no guides and the energy is free to radiate in all directions. In radiotelegraphy the surface of the earth acts as a lower guide, whilst the partially ionized upper strata of the atmosphere undoubtedly act to some extent as an upper guide confining the radiated energy within the comparatively narrow space between them.

The current that flows in a conductor whenever it is being used to transmit energy causes a continual dissipation of energy which is supplied by transmission into the conductor from the surrounding space. This transmission of energy into the conductor follows exactly the same laws as the ordinary transmission along the line. It is well known that the alternating current propagated along a telephone line suffers attenuation and that if the line is long enough and the frequency high enough no appreciable power may ever reach the distant end. Similarly with the power transmitted into the conductor, if the conductor is thick enough and the frequency high enough no power may ever reach the centre or even penetrate beyond a thin outer layer. In the ordinary telephone transmission the energy is propagated through a medium of air or gutta-percha; here, however, the energy is propagated through copper.

Straight Round Wire.

In a previous paper* the author has shown how the well-known telephone transmission formulæ may be used to calculate the skin effect in many cases. It is there shown that in a solid round wire carrying a current of such a high frequency that the penetration is small, the ratio of the high-frequency resistance R_f to the steady-current resistance R_0 is given by the formula

$$\frac{R_f}{R_0} = \pi r \sqrt{\left(\frac{f\mu}{10^7 \rho}\right)} + 0{\cdot}25$$

* G. W. O. Howe: "The Application of Telephone Transmission Formulæ to Skin-effect Problems," *Journal I.E.E.*, 1916, vol. 54, p. 473.

where r is the radius of the wire, f the frequency, μ the permeability, and ρ the specific resistance. For copper $\mu = 1$, $\rho = 1{\cdot}7 \times 10^{-6}$ ohms per cm. cube, and

$$\frac{R_f}{R_0} = \pi r \sqrt{\left(\frac{f}{1{,}700}\right)} + 0{\cdot}25$$

$$= 0{\cdot}038\, d\sqrt{f} + 0{\cdot}25$$

where d is the diameter of the wire.

Hence if R_f/R_0 is plotted against $d\sqrt{f}$ the graph is a straight line as shown in Fig. 1. For values of $d\sqrt{f}$ less than 32, or values of R_f/R_0 less than 1·5, the penetration into the wire is so great that the assumptions made in establishing the formula are no longer tenable. Even in this case, however, the problem can be solved by applying the graphical method so frequently employed in studying telephonic transmission problems. The line is divided into a number of sections by assuming its leakage and capacity to be concentrated at a number of equidistant points. The current and potential difference at the receiving end are assumed and those at any point of the line determined by constructing a vector diagram section

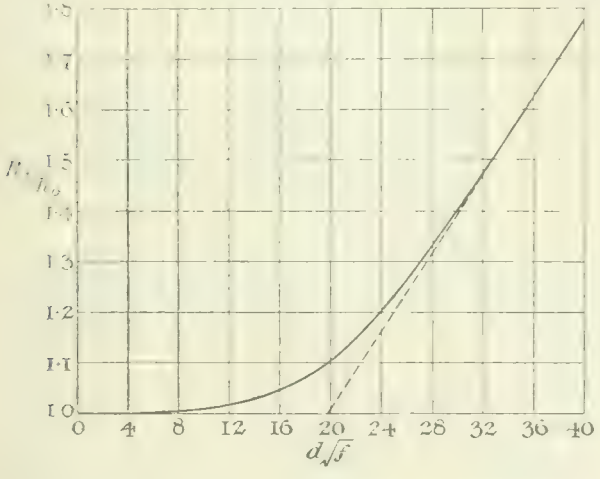


FIG. 1.

Resistance to alternating current / Resistance to continuous current for straight round copper wire.

If $d\sqrt{f}$ exceeds 32; $R_f/R = 0{\cdot}038\, d\sqrt{f} + 0{\cdot}25$.

by section, commencing at the receiving end and gradually working back along the line. This method was applied to the determination of skin effect in the paper already referred to, from which Fig. 2 is reproduced. Complete vector diagrams are there given for a 2 cm. round copper rod carrying alternating currents at frequencies of 159 and 1,590 respectively, but the results are equally applicable to any other size of copper wire provided the frequency is such that the value of $d\sqrt{f}$ is the same. In the first example $d\sqrt{f} = 25{\cdot}22$ and R_f/R_0 is found to be 1·238, whereas in the second example $d\sqrt{f} = 79$ and R_f/R_0 is found to be 3·035. In this latter example the result is too low, since for such a high value of $d\sqrt{f}$ the formula $0{\cdot}038\, d\sqrt{f} + 0{\cdot}25$ is very accurate, and it gives the value 3·28. The accuracy of the graphical method depends on the number of sections into which the line is subdivided and on the scale and accuracy of the drawing. The diagram also gives the high-frequency inductance of the wire in so far as it is modified by the alternating current. The magnetic flux external to the wire is, of course, unaltered by the skin effect. The vector diagram is in-

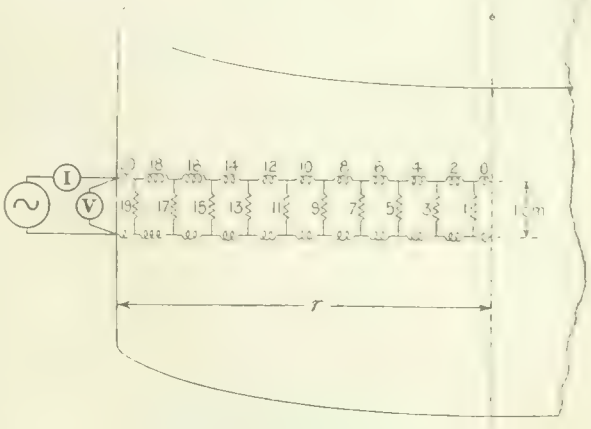
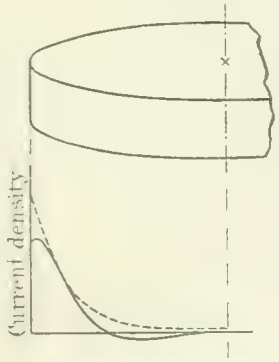


FIG. 2.

structive in showing how the magnitude and phase of the current vary with increasing depth. This is shown in Fig. 3 for $d\sqrt{f} = 79$. It is seen that at the moment of



Copper $d\sqrt{f} = 79$.

FIG. 3.—Curves showing maximum value (dotted) and value at moment of maximum total current (full line).

maximum current the central portion of the wire is carrying current in the reverse direction.

PARALLEL STRIPS.

When it is desired to keep the inductance of a circuit as low as possible, parallel strips placed close together are frequently employed. A cross-section of such a circuit is shown in Fig. 4. The current is concentrated towards the inner faces and the magnetic field is distributed as shown. If the frequency is so high that the current density at the back of the strips is practically zero, this is the simplest of all skin-effect calculations; it is considered in detail on pages 473 to 475 of the previous paper. The resistance

and losses are shown to be the same as if the total current were distributed uniformly over a layer of depth t where

$$t = \frac{1}{2\pi}\sqrt{\frac{10^9\rho}{f\mu}}$$

For copper at a frequency of a million, $t = 0{\cdot}066$ mm. If the frequency and the thickness of the strips are such that the current penetrates appreciably throughout the whole cross-section, the problem is analogous to that of the telephone line when the current is not attenuated to zero before arrival at the far end, in which case a reflected wave is superposed upon the forward wave. The formulæ for this case are well known and are used daily by telephone and alternating-current power-transmission engineers. They are employed on pages 478 and 479 of the previous

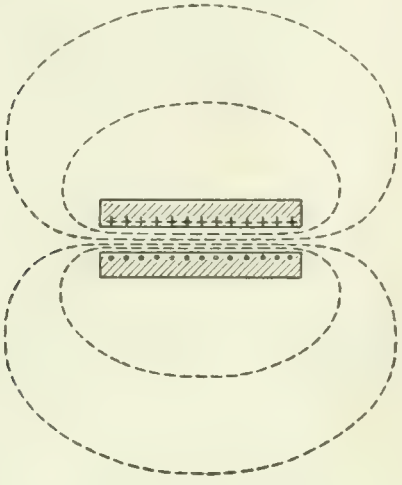


Fig. 4.

paper to calculate the current density at different depths and the resultant resistance. It is shown that

$$\frac{R_f}{R_0} = \frac{\beta\tau}{\gamma}$$

where $\beta = 2\pi\sqrt{\left(\frac{f\mu}{10^9\rho}\right)}$

τ = the thickness of the strip, and

$$\gamma = \frac{\cosh 2\beta\tau - \cos 2\beta\tau}{\sinh 2\beta\tau + \sin 2\beta\tau}$$

For small values of $2\beta\tau$, that is, for low frequencies or very thin strips, this reduces to

$$\frac{R_f}{R_0} = 1 + \frac{2}{3}\cdot\frac{(2\beta\tau)^4}{5!}$$

which for copper may be written

$$\frac{R_f}{R_0} = 1 + 47{\cdot}5\,(\tau\sqrt{f})^4\,10^{-6}$$

The value of R_f/R_0 for any value of $\beta\tau$ can be read directly off the curve in Fig. 6.

Tubular Conductors.

When the frequency is such that the current is confined to the outer skin of a round conductor, material can be saved by using a tube. If the thickness of the wall is such that the current density at the inner surface is negligible the resistance will be the same as if the conductor were solid; if, however, the wall is so thin that the current density is appreciable throughout, the above formula for the strips can be applied. τ is then the radial thickness of the wall, which should not exceed one-third of the radius.

Single-layer Cylindrical Coils.

Formulæ for the high-frequency resistance of single-layer solenoids have been given by Max Wien,* Sommerfeld,† Louis Cohen,‡ Nicholson,§ and Picciati.‖ A few trial applications of the formula obtained by Nicholson show it to give impossible results in any practical case. In the present paper the results obtained by the other authors are compared among themselves and with the small amount of experimental evidence which has been published. Further experimental results are given which enable the high-frequency resistance to be predicted with reasonable accuracy. In addition to the experiments described in some of the papers referred to above, experimental results have been published by Battelli and Magri,¶ Black,** Fleming,†† and Esau.‡‡

Coils wound with rectangular wire.—In the previous paper the author has shown that the resistance of a long coil closely wound with a single layer of square or rect-

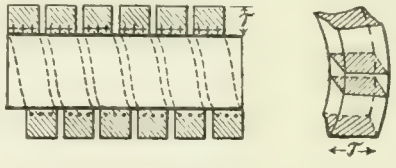


Fig. 5.

angular wire as shown in Fig. 5 is given accurately by the same formula as that already found for the parallel strips, viz.

$$\frac{R_c}{R_0} = \frac{\beta\tau}{\gamma}$$

where τ is the radial thickness of the wire. The values of R_c/R_0 are plotted in Fig. 6 against values of $\beta\tau$.

On the right of Fig. 5 are shown the fictitious planes of infinitely good conducting material which may be imagined to be embedded in the wire to serve as lines to transmit the energy radially outwards into the piece of copper between them.

If there is a small space between adjacent turns, the magnetic field within the conductor and in the spaces between the turns will still be approximately linear and parallel to the axis of the coil, but for a given current density the magnetic flux density will be reduced. The same result would be caused by a decrease in the permeability and either would lead to an increased penetration. If the wire has a square section of side τ cm. and if S is the number of turns per cm., $S\tau$ is the fraction of the axial length occupied by the conductor, the remainder

* *Annalen der Physik*, 1904, vol. 14, p. 1
† *Ibid.* 1904, vol. 15, p. 673, and 1907, vol. 24, p. 609.
‡ *Bulletin of the Bureau of Standards*, 1907, vol. 4, p. 162.
§ *Proceedings of the London Physical Society*, 1909, vol. 22, p. 114; and *Philosophical Magazine*, 1910 vol. 19, p. 77.
‖ *Il Nuovo Cimento*, 1906, p. 351.
¶ *Philosophical Magazine*, 1903, ser. 6, vol. 5, p. 1.
** *Annalen der Physik*, 1906, vol. 19, p. 157.
†† *Journal I.E.E.*, 1910, vol. 44, p. 344.
‡‡ *Annalen der Physik*, 1911 vol. 34, pp. 57, 81, and 547.

being occupied by insulation or air space. The penetration would be the same if the turns were close together, but the permeability of the material reduced from 1 to

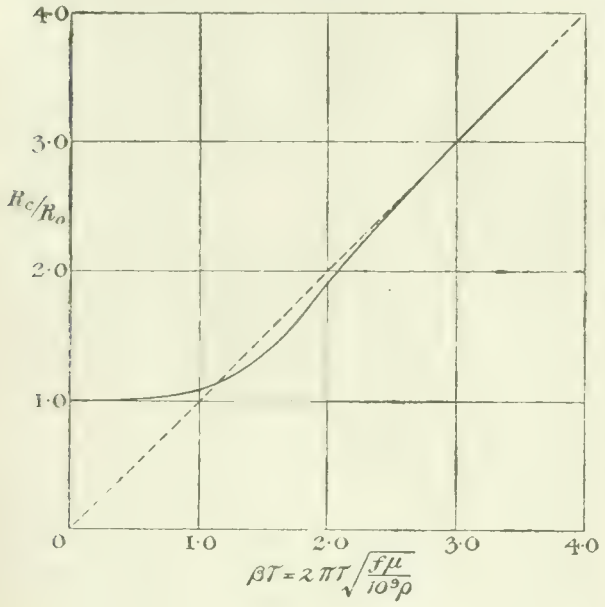


FIG. 6.

$S\tau$. Assuming the conductor to have unit permeability, β would be reduced from

$$2\pi\sqrt{\left(\frac{f}{10^9\,\rho}\right)} \quad \text{to} \quad 2\pi\sqrt{\left(\frac{S\tau f}{10^9\,\rho}\right)}$$

It will be seen from Fig. 6 that the values of the ratio R_c/R_o are practically independent of $\beta\tau$ for values of the latter up to 0·6, but directly proportional to $\beta\tau$ if it exceeds 2·5. Hence when the frequency is so low that the skin effect is only slight the pitch of the turns has little effect, but at very high frequencies where the skin effect is very pronounced, the ratio R_c/R_o is proportional to $\sqrt{(S\tau)}$. This is only strictly true when $S\tau$ differs but little from unity.

For many purposes it is convenient to consider the ratio of the high-frequency resistance R_c of the coil to the high-frequency resistance R_f of the same wire when straight.

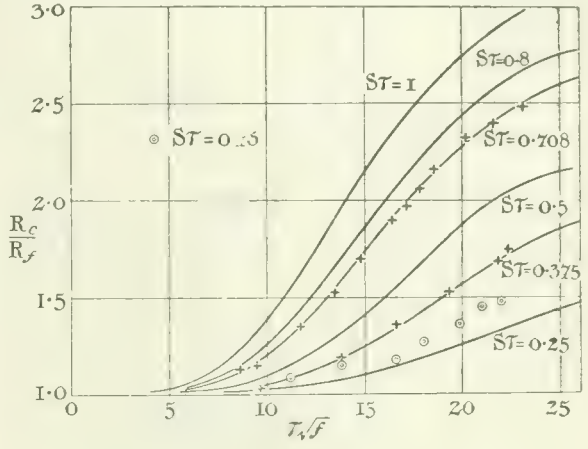


FIG. 7.—Coils wound with square wire.

In the present case this would necessitate a knowledge of the ratio R_f/R_o for a straight wire of square section. At low frequencies the resistance of a square wire approximates to that of a round one of equal cross-section, whereas at very high frequencies its resistance is inversely proportional to its periphery and, neglecting the fact that the current density is slightly greater near the edges than near the middle of the faces, approximates to that of a round

TABLE I.

Calculated Values of R_c/R_f for Coils wound with Square Wire.

$\tau\sqrt{f}$	R_f/R_o	$S\tau = 1$		$S\tau = 0·8$		$S\tau = 0·5$		$S\tau = 0·25$	
		R_c/R_o	R_c/R_f	R_c/R_o	R_c/R_f	R_c/R_o	R_c/R_f	R_c/R_o	R_c/R_f
2	1	1	1	1	1	1	1	1	1
4	1	1·012	1·012	1·006	1·006	1	1	1	1
6	1·001	1·06	1·06	1·04	1·039	1·016	1·015	—	—
8	1·003	1·18	1·175	1·12	1·115	1·04	1·035	1·012	1·01
10	1·007	1·39	1·38	1·27	1·26	1·11	1·1	—	—
12	1·015	1·69	1·667	1·49	1·47	1·22	1·2	1·06	1·044
14	1·027	2·06	2·006	1·78	1·735	1·37	1·335	—	—
16	1·045	2·4	2·3	2·1	2·01	1·57	1·5	1·18	1·13
18	1·071	2·72	2·54	2·4	2·24	1·81	1·69	—	—
20	1·104	3·03	2·745	2·7	2·44	2·08	1·885	1·39	1·26
24	1·200	3·64	3·033	3·26	2·72	2·55	2·125	1·69	1·41
30	1·399	4·56	3·26	—	2·92	—	2·31	2·23	1·59
40	1·774	6·08	3·43	—	3·06	—	2·43	3·03	1·71
60	2·569	9·12	3·56	—	3·18	—	2·52	4·56	1·776
120	4·888	18·24	3·74	—	3·34	—	2·64	9·12	1·87
200	7·98	30·4	3·81	—	3·41	—	2·69	15·2	1·905

wire of the same periphery. For intermediate cases it will lie somewhere between these two limiting values. Now the area of a circle inscribed in a square has an area $\pi/4$ of that of the square and also a periphery $\pi/4$ of that of the square. Hence a round wire equal in diameter to the side of a square wire has $4/\pi$ times its resistance both at very low and at very high frequencies. It may be assumed therefore as an approximation that this ratio is constant at all frequencies. The resistance of linear conductors of square section has been investigated theoretically and experimentally by H. W. Edwards.* It will be found, however, that the inscribed circle method gives results in as good agreement with his observations as his own theoretically established formula. The biggest difference between the calculated and observed results is about 4 per cent for values of $\tau\sqrt{f}$ ranging from 0 to 42.

The values of R_c/R_o and R_c/R_f have been calculated for a solenoid of square wire with $S\tau = 1{\cdot}0$, $0{\cdot}8$, $0{\cdot}5$ and $0{\cdot}25$ respectively, that is, for coils in which τ is 100, 80, 50 and 25 per cent of the pitch of the turns. The results are

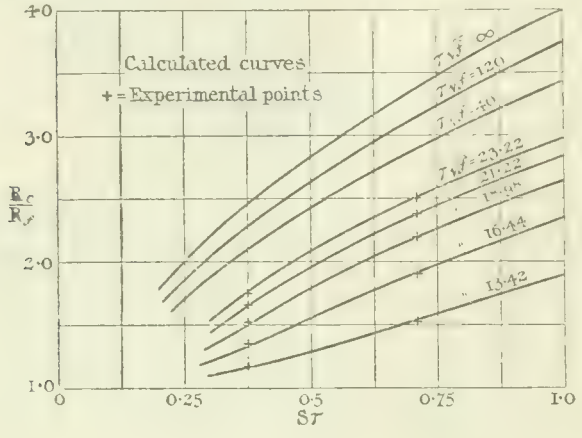


FIG. 8.—Coils wound with square wire.

given in Table 1 and Figs. 7 and 8. The curves are calculated by the above formulæ but the points marked are experimental results obtained by Esau (*loc. cit.*) who measured the high-frequency resistance of single-layer coils of square wire. For the sake of comparison the curves have also been drawn for the values of $\tau\sqrt{f}$ and of $S\tau$ which were employed by Esau. It will be seen that the agreement is very good except for the lowest values of $S\tau$. Since the calculation is based on the assumption that $S\tau$ is not much less than unity, the accuracy with which the observed points lie on the curve when $S\tau = 0{\cdot}375$ is somewhat surprising, more especially in view of the enormous discrepancies when $S\tau = 0{\cdot}161$. It must be remembered that it has been assumed that the coils are long and that the diameter is large compared with the pitch.

Solenoid wound with round wire.—If the coil is wound with round wire the problem is more difficult, since, even when closely wound, the distribution of the current over the cross-section of the wire is not cylindrical, or, in other words, the energy is not transmitted into the conductor in a direction normal to the axis of the coil. The only writers who appear to have attacked the problem rigidly are Picciati and Sommerfeld. Others have considered the problem, but have assumed, either that the wire is square, or that the current distribution in the round wire is similar to that in the square wire. Cohen assumed that the results obtained by him for square wire could be applied to round wire. His formula is only applicable to very closely wound coils, and if applied to coils in which $S\,d = 0{\cdot}5$, that is, in which the space between the wires is equal to the diameter of the wire, it may lead to coil resistances less than that of the wire when straight. As an example, the dotted curve in Fig. 9 is calculated by Cohen's formula for $d\sqrt{f} = 56{\cdot}4$. At low frequencies, however, Cohen's formula gives good results, even for coils which are not closely wound, as can be seen from the lower dotted curves in Fig. 9 for $d\sqrt{f}$ equal to 17·8 and 12·0 respectively.

Cohen's formula is as follows:

$$R_c = R_o + R' \text{ per cm. of wire, where}$$

$$R' = 64\, S^2 \omega^2 d^2 \sigma \sum_{n=1}^{n=\infty} \frac{1}{n^2 (\alpha_n^2 + \beta_n^2)\, a_n}$$

where $2\alpha^2 = m^2 + \sqrt{(m^4 + 16\,\pi^2 \alpha^2 \omega^2)}$,

$2\beta^2 = -m^2 + \sqrt{(m^4 + 16\,\pi^2 \sigma^2 \omega^2)}$,

σ = conductivity (C.G.S.) = 1/1,700 for copper,

and $m = n\,\pi/d$ ($n = 1, 3, 5$, etc.).

At very high frequencies $\alpha^2 = \beta^2 = 2\,\pi\,\alpha\,\omega$ and

$$R' = 6{\cdot}1\, S^2 d \sqrt{(f\sigma)}$$
$$= 252\, S^2 d \sqrt{f} \times 10^{-9} \text{ ohms per cm. for copper}$$

Also, at very high frequencies $R_c = R'$ and

$$R_f / R_o = (\pi d/2) \sqrt{(f\sigma)}$$

therefore

$$R_c/R_f = 3{\cdot}05\, S^2 d^2$$

If this were so, on pulling a closely-wound coil out until the pitch was twice the diameter of the wire ($S\,d = 0{\cdot}5$), the resistance to very high frequencies would be reduced to a quarter, and would be less than that of the wire when straight. It is obvious, therefore, that Cohen's formula for high frequencies cannot be used unless $S\,d$ is very nearly unity.

For low frequencies M. Wien obtained the formula

$$R_c/R_o = 1 + 0{\cdot}272\, \pi^2 \omega^2 \sigma^2 l^4 (2\,\pi\, r\, S)^2$$

which, for copper, may be written

$$R_c/R_o = 1 + 23 \cdot 10^{-6} (d\sqrt{f})^4 \cdot (S\,d)^2$$

This is somewhat similar to the formula for low frequencies obtained by Sommerfeld, viz.

$$\frac{R_c}{R_o} = 1 + 0{\cdot}25\, \pi^2 \omega^2 \sigma^2 l^4 \left\{ \frac{1}{3} + (2\,\pi\, r\, S)^2 + \frac{(2\,\pi\, r\, S)^4}{216} + \ldots \right\}$$

which, for copper, may be written

$$\frac{R_c}{R_o} = 1 + 2{\cdot}12 \times 10^{-6} (d\sqrt{f})^4 \left\{ \frac{1}{3} + \pi^2 (S\,d)^2 + \frac{\pi^4}{216} (S\,d)^4 + \ldots \right\}$$

If $S\,d$ is not much less than unity, the second term is much bigger than any other, and we have approximately

$$R_c/R_o = 1 + 21 \times 10^{-6} (d\sqrt{f})^4 (S\,d)^2$$

* *Electrician*, 1912, vol. 68, p. 728; and *Physical Review*, 1911, vol. 33, p. 184.

which is practically the same as Wien's formula. As mentioned in connection with parallel strips the accurate formula for closely coiled square wire, viz. $R_c/R_o = \beta\tau/\gamma$, can be modified for small values of $\beta\tau$ by expanding the trigonometrical and hyperbolic functions and neglecting the higher powers of $\beta\tau$; in this way one obtains

$$\frac{R_c}{R_o} = 1 + \frac{2(2\beta\tau)^4}{3\ \ 5!}$$
$$= 1 + 47{\cdot}5 \times 10^{-6}(\tau\sqrt{f})^4 \text{ for copper.}$$

in exact agreement with Wien and Sommerfeld. This formula is only applicable to low frequencies ($d\sqrt{f}$ less than 10).

At very high frequencies the replacement of closely-wound round wire by square wire of equal section also leads to results almost identical with those obtained by Sommerfeld; thus from Fig. 8 for $\tau\sqrt{f} = \infty$ and $S\tau = 0{\cdot}886$, $R_c/R_f = 3{\cdot}76$, whereas Sommerfeld calculated 3·73 for closely-wound round wires at infinitely high frequencies. It should be mentioned that Sommerfeld only succeeded

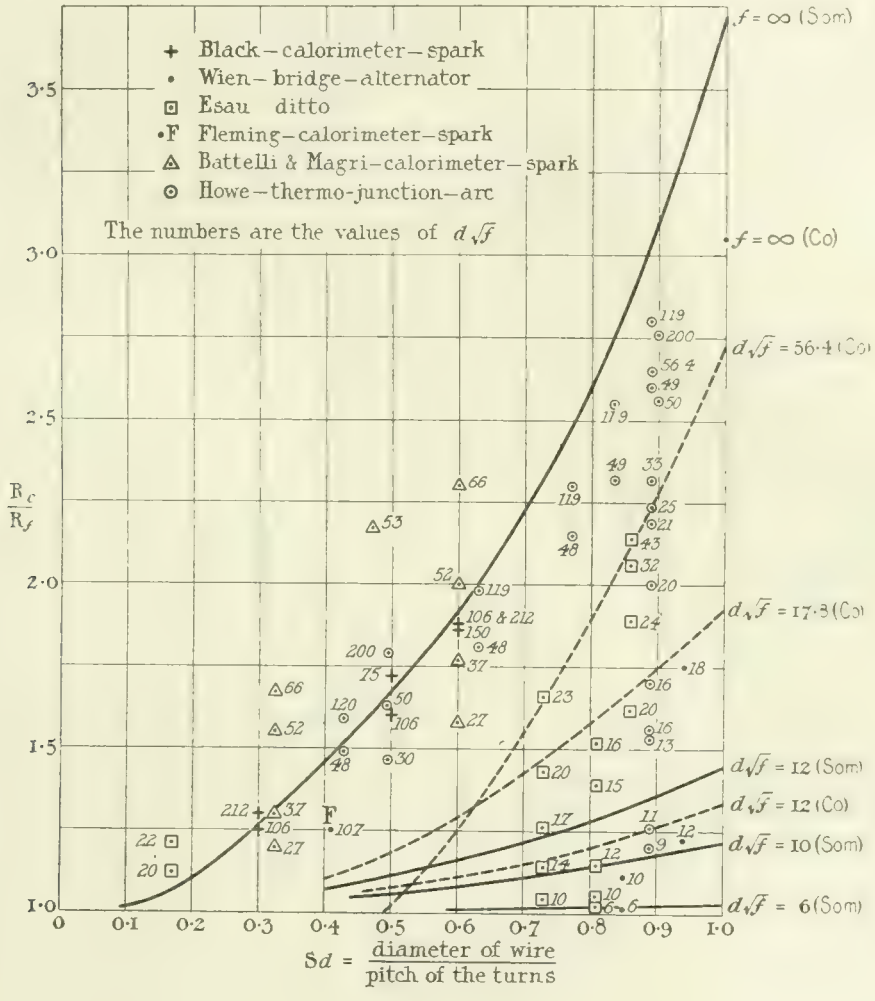


FIG. 9.

We have also shown that, if not closely wound, the effect is similar to that of reducing the permeability from 1 to $S\tau$, which would reduce β^4 in the ratio of 1 to $(S\tau)^2$, and give the formula

$$R_c/R_o = 1 + 47{\cdot}5 \times 10^{-6}(\tau\sqrt{f})^4 \cdot (S\tau)^2$$

If this formula is assumed to hold approximately for round wires of equal cross-section, we have

$\tau = 0{\cdot}886\,d$; $(\tau\sqrt{f})^4 = 0{\cdot}617(d\sqrt{f})^4$; $(S\tau)^2 = 0{\cdot}785(Sd)^2$

and $R_c/R_o = 1 + 23 \times 10^{-6}(d\sqrt{f})^4 (Sd)^2$

in solving the problem for the case of the turns in actual contact, i.e. for $Sd = 1$; for values of Sd less than unity, he used the experimental results of T. P. Black. We are therefore entirely dependent on experimental observations except for certain special cases. The results obtained by various experimenters have been plotted in Fig. 9; beside each point is given the value of $d\sqrt{f}$. The results are very discordant but it must be remembered that the measurements have been made by different methods and with different sources of alternating currents; some with damped and some with undamped oscillations.

The curves shown have been calculated by the various formulæ to which reference has been made. None of these formulæ take into account the effect of the diameter of the coil, which may be an important factor for small values of S d; the formulæ assume the coils to be very long in comparison with their diameters, and they would obviously be very inaccurate if applied to narrow coils of large diameter (see section on "Short Coils").

Experimental.

A number of measurements of the high-frequency resistance of coils have been made at the Imperial College of Science and Technology during the last three or four years by the author and by several research students, especially Mr. Smith-Rose, B.Sc., and Mr. W. Greenwood, B.Sc. The method finally adopted was as follows: The coil was supported horizontally by a small glass rod in a large wooden box, about 1 yard cube, containing heating apparatus* (carbon filament lamps) controlled by a thermostat, whereby the temperature in the box could be maintained constant. The temperature rise of the coil was determined by means of a thermo-junction of very fine wires soldered to a point of the coil near its centre; these wires could be disconnected from the galvanometer circuit except when a reading was to be made. The galvanometer deflections were determined for various steady direct currents which were kept constant until the temperature reached its steady value. Alternating current was then substituted for the direct and the galvanometer deflection determined when the temperature had become steady. If I_o is the direct current required to give the same temperature rise as the alternating current I_c, then $I_o^2 R_o = I_c^2 R_c$. The value of I_c was read on a hot-wire ammeter which showed no sign of skin effect at the frequencies employed and which was calibrated after each test. The possibility of the galvanometer reading being affected by capacity currents flowing from the solenoid along the thermo-junction wires to the galvanometer can be avoided by connecting the galvanometer leads to the thermo-junction wires after the main circuit has been opened. By reading the deflection at definite intervals after opening the circuit a cooling curve can be plotted and produced backwards to give the value corresponding to zero time. This extrapolation can be obviated by adopting the same procedure when calibrating the solenoid with direct current and always taking the galvanometer deflection, say, 10 seconds after opening the main circuit.

* This refinement was found unnecessary and was discontinued.

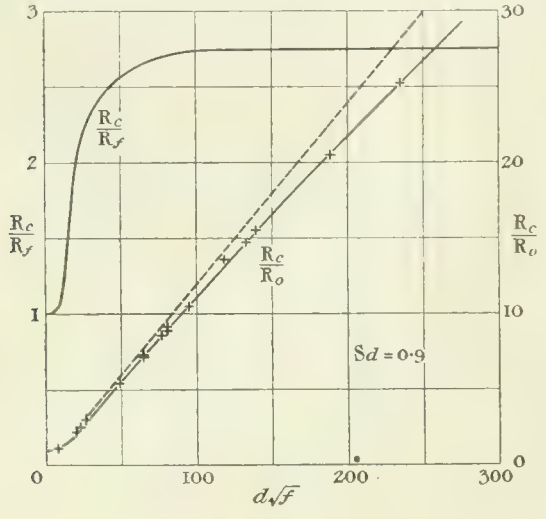


Fig. 10.

The alternating current was usually obtained from a Poulsen arc, to the oscillatory circuit of which the solenoid was coupled by means of an air-core transformer. The frequency was determined in the ordinary way by means of resonant circuits of accurately calculable frequency, except at the lowest frequencies which could be determined acoustically by comparing the note emitted by the arc, with standard tuning forks and syrens.

Tests were made to discover the presence of harmonics; at low frequencies these were not troublesome but at very high frequencies it was found impossible to keep them down to a negligible amplitude. The obvious method of putting a condenser in the secondary circuit and tuning it to the desired frequency, is very troublesome in practice, on account of the inconstancy of the arc frequency. The presence of harmonics undoubtedly constitutes the principal source of possible error when a Poulsen arc is employed as the source of the alternating current.

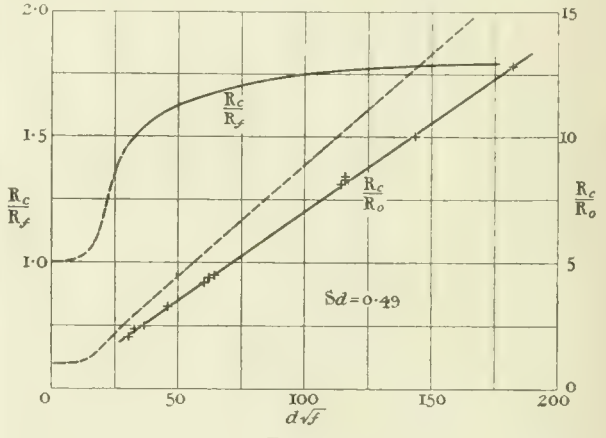


Fig. 11.

The results obtained by this method are shown in Figs. 10 and 11. In Fig. 10 the coil consisted of 92 turns of 0·264 cm. wire; the total length of the coil was 26·9 cm. and its external diameter 2·86 cm. The ratio of the diameter of the wire to the pitch of the turns $= Sd = 3{\cdot}42 \times 0{\cdot}264 = 0{\cdot}9$. A fair curve has been drawn through the observed points. A square wire of equal cross-section would have a side $\tau = 0{\cdot}234$, therefore $S\tau = 0{\cdot}79$ and $\sqrt{(S\tau)} = 0{\cdot}89$. Applying the formula for a coil wound with square wire, we have

$$\frac{R_c}{R_o} = \frac{\beta\tau}{\gamma}$$

where $\beta = 0{\cdot}152\sqrt{f} \times \sqrt{(S\tau)}$, $\therefore \beta\tau = 0{\cdot}0316\sqrt{f}$. The corresponding values of R_c/R_o can be read off the curve in Fig. 6. These calculated values for the equivalent square wire are shown by the dotted curve in Fig. 10; they are about 11 per cent greater than the measured values of R_c/R_o.

In Fig. 11 the coil consisted of 62 turns of wire 0·163 cm.

diameter with a total length of 20·4 cm. and a pitch of 0·33 cm. $Sd = 0·49$. A square wire of equal cross-section would have a side $\tau = 0·144$ cm., $S\tau = 0·436$, and $\surd(S\tau) = 0·66$. Therefore

$$\frac{R_c}{R_0} = \frac{\beta\tau}{\gamma}$$

where $\beta = 0·152\surd f \times \surd(S\tau)$, $\therefore \beta\tau = 0·1044\surd f$. The dotted curve shows the values of R_c/R_0 calculated in this way. They are 26 per cent higher than the measured values.

Multi-layer Coils.

Exigencies of space sometimes compel the designer of radio apparatus to employ coils with more than a single layer of wire. The inductance increases as the square of the number of turns in a given length, whereas the resistance to steady currents is directly proportional to the turns. At high frequencies, however, the resistance may be greatly increased by the addition of a second or third layer.

Consider a long solenoid wound with three lengths of square wire as shown in Fig. 12. Numbering the layers from the outside, the magnetic field in the first annular space is due only to the current in the first layer, that in the second annular space is due to the currents in the two outer layers, and that inside the solenoid to the total current. These fields are therefore in the ratio of 1 : 2 : 3. If the frequency is very high the currents will be such as to prevent the penetration of these magnetic fields into the wires. The current I will be confined to the inner skin of the outer layer, the lost energy being transmitted radially into the wire from the annular gap. The flux will be prevented from penetrating very deeply into the second layer by a current I in the reverse direction in its outer skin, and a current 2 I—the field being twice as strong—in the forward direction in its inner skin. Similarly in the inner layer the penetration of flux is prevented by currents of -2 I and $+3$ I in the outer and inner skins respectively. The resultant current is of course the same in every layer, viz. I. Since the power lost is proportional to the square of the current the effective resistances are as follows :—

Table 2.

Number of Layers	Current in Outer and Inner Skin	Relative Power dissipated in Each Layer	Relative Power dissipated in All Layers	$\frac{R}{R_0}$	Relative Inductance
1	0 I	0 1	1	$\beta\tau$	1
2	$-$ I 2 I	1 4	5	$3\ \beta\tau$	4
3	-2 I 3 I	4 9	13	$6\frac{1}{3}\beta\tau$	9
4	-3 I 4 I	9 16	25	$11\ \beta\tau$	16
5	-4 I 5 I	16 25	41	$17\ \beta\tau$	25

Hence if the size of wire and the frequency are such that the skin effect is very pronounced, the effective resistance increases much more rapidly than the inductance as the number of layers is increased. When, however, the penetration into the wires is considerable, the calculation of the effective resistance is much more complicated. The sketch on the right of Fig. 12 shows

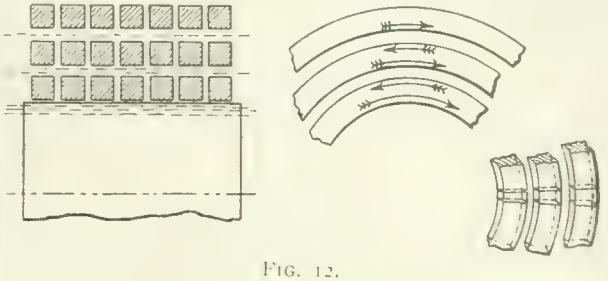


Fig. 12.

the fictitious transmission lines—slightly divergent planes—by which we may imagine the energy to be transmitted into that portion of the conductor which lies between them. Except in the outer layer the transmission lines have power supplied to them at both ends, with the condition that the line currents at the two ends are in phase and in a definite ratio k, which is 2 for the second layer, 1·5 for the third, and $n/(n-1)$ for the nth layer. This problem is

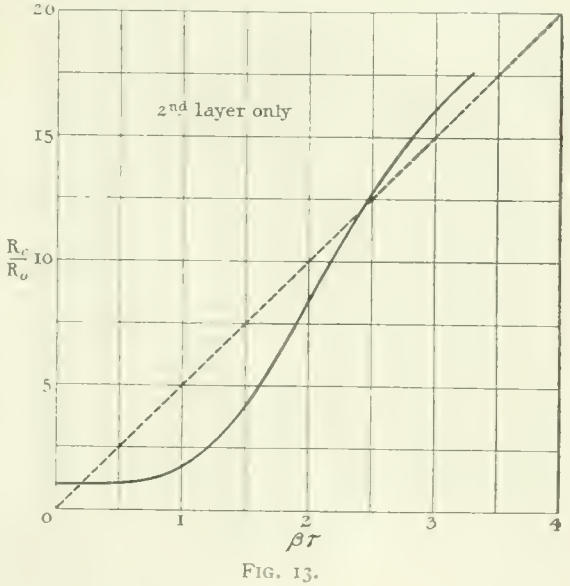


Fig. 13.

worked out in the appendix where it is shown that the power dissipated in any layer per axial centimetre is

$$P = i_2^2 \beta\rho\, F(\beta\tau, k)$$

where i_2 is the imaginary line current supplied at the outer end of the fictitious transmission line, ρ the specific resistance, τ the radial depth of each layer, and $F(\beta\tau, k)$ a complicated function, values of which are tabulated in the Appendix.

If I be the actual resultant current in the coil per axial centimetre, the value of i_2 for the nth layer is $(n-1)$ I, and

$$P = (n-1)^2 I^2 \beta\rho\, F(\beta\tau, k)$$

whereas with an equal direct current

$$P = I^2 \frac{\rho}{\tau}$$

Hence for the nth layer

$$R_c/R_o = (n-1)^2 \beta\tau F(\beta\tau, k)$$

The values of R_c/R_o have been calculated by this formula for the second, third, and fourth layers, and the results are tabulated both for the individual layers and for the complete coils.

As an example the values of R_c/R_o for the second layer have been plotted in Fig. 13, the curves for the other layers being very similar but to a different scale.

TABLE 3.

Values of R_c/R_o.

$\beta\tau$	First Layer	Second Layer	Two-layer Coil	Third Layer	Three-layer Coil	Fourth Layer	Four-layer Coil
0·5	1·000	1·05	1·02	1·13	1·06	1·27	1·11
1·0	1·086	1·73	1·41	3·01	1·94	4·96	2·70
1·5	1·376	4·17	2·77	9·76	5·10	18·13	8·36
2·0	1·897	8·36	5·13	21·25	10·50	40·70	18·05
2·5	2·475	12·70	7·59	33·15	16·11	—	—
3·0	2·988	16·08	9·53	42·12	20·40	81·54	35·68

The curves in Fig. 14 give the values of R_c/R_o for coils with various numbers of layers. For high values of $\beta\tau$ the curves approximate to the dotted lines in accordance with the values given in Table 2.

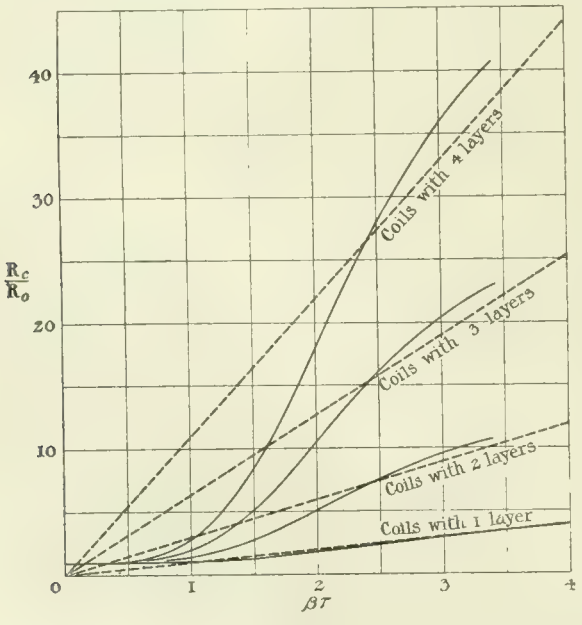


FIG. 14.

These curves refer to long coils closely wound with square or rectangular wire and corrections must be applied for the spaces between adjacent turns, and for the coil not being very long compared with its diameter. The results are not affected, however, by the space between adjacent layers. As we have shown in the case of single-layer coils, the effect of spacing between adjacent turns, if not excessive, can be allowed for by taking the value of R_c/R_o for $\beta\tau\sqrt{(S\tau)}$ instead of for $\beta\tau$, where S is the number of turns per centimetre and τ is the side of the square. With round wire an approximate result can be obtained by assuming it to be replaced by square wire of equal sectional area.

THE USE OF MULTIPLY STRANDED INSULATED WIRE.

It is a common practice to make wires intended for high-frequency currents of a large number of small wires, each separately insulated and the whole so stranded that every individual wire occupies in turn the same relative position in the composite wire. In this way the current is forced to distribute itself uniformly between the individual wires. It must not be assumed, however, that because these wires are of so small a diameter that when used alone they exhibit but little skin effect, the composite wire will therefore have the same resistance to high-frequency currents as to direct currents. The author has discussed this subject in detail in a paper read before the Royal Society in 1917,* and formulæ are there given both for straight wires and for long single-layer coils. It is shown that the ratios R_c/R_o and R_f/R_o are in many cases so great that better results would be obtained by using a solid wire even of the same copper section. The solid wire, can, however, have a much larger cross-section of copper and still occupy the same space in a coil. Not only is the solid wire much cheaper but the making of end connections and tappings does not introduce the difficulties met with in dealing with stranded conductors. In many cases in which the stranded wire has a theoretical advantage this is so small as to make it doubtful whether the use of stranded wire with its attendant disadvantages is justified.

The cause of the high effective resistance of the stranded wire is the eddy-current loss in the individual wires due to the magnetic field produced by all the other wires. These losses are calculated in the paper referred to and the values of R_f/R_o and R_c/R_o tabulated in a form convenient for practical use. As an example of the application of the formulæ there established the following case is taken. Lindemann† measured the high-frequency resistance of a coil of 14 turns of stranded conductor wound on a glass cylinder 24 cm. diameter. The conductor consisted of 180 enamelled wires 0·012 cm. diameter, arranged $3' \times 3 \times 4 \times 5$, i.e. five single wires were first twisted together, then four of these conductors, and so on. The formula for single layer solenoids is

$$R_c = R_o\left\{1 + 35{\cdot}6 \times 10^{-6}\, n f^2 d^4 a (S\tau)^2\right\}$$

where n = number of wires, d = their diameter,
a = space factor.

The frequency $f = 900{,}000$. Assuming $a = 0{\cdot}5$ and $S\tau = 0{\cdot}9$, since although the turns are in contact, the conductor is round and not square, we have

$$R_c = R_o(1 + 43{\cdot}1) = 44{\cdot}1\ R_o$$

* *Proceedings of the Royal Society*, A, 1917, vol. 93, p. 468.

† LINDEMANN, *Deut. Phys. Gesell.*, 1909, p. 682; 1910, p. 572; *Jahrbuch*, 1911, p. 501. See also MEISSNER, *Jahrbuch*, 1909, p. 57; MOLLER, *Annalen der Physik*, 36, p. 738, 1911; *Jahrbuch*, 1914, p. 32.

This is for a very long solenoid, whereas the length of Lindemann's coil was only about one-eighth of the diameter. For a very narrow coil the magnetic field H′ at the inner side of the wire is little more than half its value H in a long solenoid for the same number of ampere-turns per centimetre and the eddy-current loss varies as the square of the magnetic field. From Fig. 16 it is seen that for $l/D = \frac{1}{8}$, $(H'/H)^2 = 0{\cdot}32$ and therefore

$$R_c/R_o = 1 + (0{\cdot}32 \times 43{\cdot}1) = 1 + 13{\cdot}8 = 14{\cdot}8$$

Lindemann's measurements gave $R_c/R_o = 15$. Now a solid wire with the same cross-section of copper has a diameter of 0·16 cm. At the same frequency $d\sqrt{f} = 153$, and R_c/R_o for a long solenoid would lie between 13 and 14. Hence in this case the stranded conductor is inferior to the solid wire of the same copper section and would be still more inferior to the larger copper wire which could be wound in the same space.

Another interesting fact which was shown in the paper referred to was that the minimum high-frequency resistance was not obtained by putting as many individual wires as possible into the available space, but that there is an optimum space-factor beyond which the addition of more wires increases the resistance.

In many cases the fine wires are not distributed uniformly throughout the cross-section of the conductor but are confined to the outer surface, the wires being plaited around a non-conducting core. The formulæ can easily be modified and applied to such cases.

The use of stranded wires in coils of more than one layer has not yet been considered but presents no difficulties. Numbering the layers from the outside the average values of H^2 in the first three layers are in the ratio of 1 : 7 : 19, and the eddy losses are proportional to these values. Hence in a two-layer coil the total eddy loss is 8 times that in a single-layer coil, whilst in a three-layer coil it is 27 times that in a single-layer coil. The ratios of the eddy loss to the steady current loss are therefore as 1 : 4 : 9, and the formulæ become :—

In a single layer coil $R_c = R_o\left\{1 + 35{\cdot}6 \times 10^{-6}\, n^2 f^2 d^4 a\, (S\tau)^2\right\}$

" two " " $R = R_o\left\{1 + 4 \times 35{\cdot}6 \times 10^{-6} n^2 f^2 d^4 a (S\tau)^2\right\}$

" three " " $R = R_o\left\{1 + 9 \times 35{\cdot}6 \times 10^{-6} n^2 f^2 d^4 a (S\tau)^2\right\}$

These formulæ assume infinitely long solenoids; if the coil is short the value must be corrected as explained under "Short Coils." The formulæ will not be accurate for values of $S\tau$ less than about 0·5.

Short Coils.

The calculated formulæ for the high-frequency resistance of coils are all based on the assumption that the coils are very long in comparison with the diameter. In a short coil the density of the magnetic flux at the inner side of the wire is less than in a long coil with the same number of ampere-turns per centimetre. The effect of spacing between adjacent turns was shown to be equivalent to a reduction of the permeability in the expression for β for a closely-wound coil. The reduction of flux density due to the coil not having infinite length can be treated in the same way. The value of R_c/R_o for a short coil can be read off the curve for a closely-wound infinitely long coil if instead of $\beta\tau$ one takes the value

$$\beta\tau\sqrt{(S\tau)}\sqrt{B'/B}$$

where B is the flux density in a long solenoid and B′ that in the short coil, the values being determined at the inner

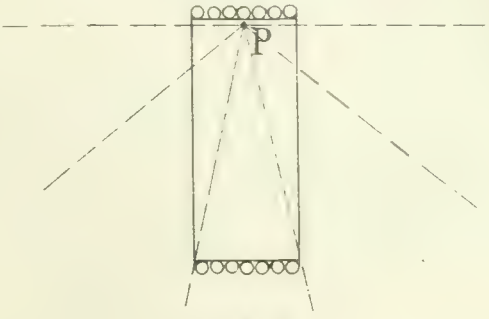


Fig. 15.

side of the wire. The correcting factor $\sqrt{(S\tau)}$ has already been discussed.

The ratio B′/B can be found in the following manner.

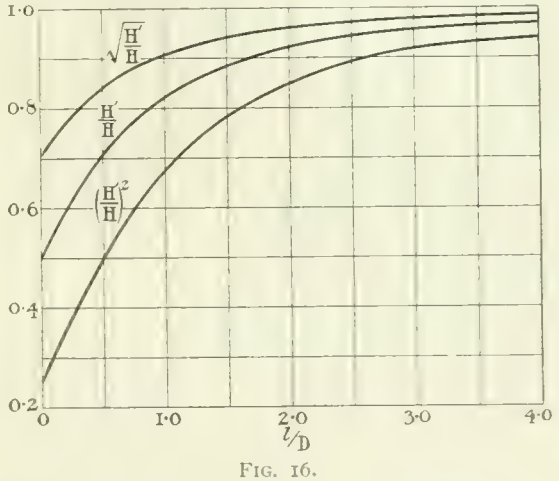


Fig. 16.

If a unit pole were placed at P in Fig. 15 a certain fraction of its 4π lines of force would pass through the ends and, in any small axial movement of the pole, would not cut the turns of the coil, whereas if the coil were infinitely long all the 4π lines would cut the turns. The work done in an axial movement of 1 cm. is a measure of

Table 4.

Correction Factors for Short Coils.

l/D	H'/H	$\sqrt{(H'/H)}$	$(H'/H)^2$
0·25	0·61	0·78	0·37
0·5	0·70	0·84	0·49
1·0	0·82	0·91	0·67
2·0	0·92	0·96	0·85
4·0	0·97	0·985	0·94

H and this is proportional to the number of lines cutting the coil. The calculation resolves itself into a determination of the solid angle subtended at P by the discs forming the ends of the coil. The author has calculated the ratio H′/H for various values of l/D and the results are shown in Table 4 and in Fig. 16.

The effect on R_c/R_f of multiplying $\beta\tau$ by $\sqrt{(H'/H)}$ may be small or great, depending on the value of $\beta\tau$, as can be seen from Fig. 6.

In the case of multiply stranded insulated wire the eddy-current loss in the individual wires is proportional to H^2. In this case the term in the expression for R_c/R_o which depends on the eddy-current loss, that is, the second term, must be multiplied by $(H'/H)^2$. An example of this correction occurred when considering the experimental result obtained by Lindemann.

APPENDIX.

Dissipation of Power in a Line Supplied from Both Ends.

$$V_1 = V_2 \cosh a\tau + i_2 \sqrt{(Z/Y)} \sinh a\tau \quad . \quad . \quad (1)$$

$$i_1 = i_2 \cosh a\tau + V_2 \sqrt{(Y/Z)} \sinh a\tau \quad . \quad . \quad (2)$$

From (2) $$V_2 = \left(\sqrt{\frac{Z}{Y}}\right) \frac{i_1 - i_2 \cosh a\tau}{\sinh a\tau} \quad . \quad . \quad (3)$$

From (1) and (3)

$$V_1 = \left(\sqrt{\frac{Z}{Y}}\right) \left\{ \frac{i_1 - i_2 \cosh a\tau}{\sinh a\tau} \cosh a\tau + i \sinh a\tau \right\} \quad (4)$$

If i_1 and i_2 are in phase and $i_1 = k i_2$, the power supplied to the line at the end (1) = P_1 where

$$P_1 = V_1 i_1 \cos\phi_1$$

$$= k i_2^2 \left(\sqrt{\frac{Z}{Y}}\right) \left\{ \frac{k - \cosh a\tau}{\sinh a\tau} \cosh a\tau + \sinh a\tau \right\}$$

(real part only) (5)

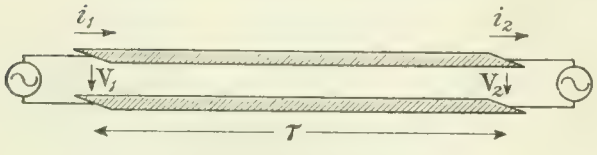


Fig. 17.

The power supplied to the end (2) of the line is from equation (3)

$$P_2 = -V_2 i_2 \cos\phi_2 = -i_2^2 \left(\sqrt{\frac{Z}{Y}}\right) \cdot \frac{k - \cosh a\tau}{\sinh a\tau}$$

(real part only) (6)

Hence the total power $P = P_1 + P_2$ = the real part of

$$i_2^2 \left(\sqrt{\frac{Z}{Y}}\right) \left\{ (k - \cosh a\tau) \left(\frac{k \cosh a\tau - 1}{\sinh a\tau}\right) + k \sinh a\tau \right\} \quad (7)$$

In the present case

$$\sqrt{\frac{Z}{Y}} = \sqrt{\left(\frac{j\omega L}{G}\right)} = \sqrt{j} \sqrt{\left(\frac{\omega L}{G}\right)} = \sqrt{2\beta\rho}\,|45^\circ = (1+j)\beta\rho$$

where $\beta = 2\pi \sqrt{\left(\frac{l\mu}{10^9 \rho}\right)}$.

Also $a = \sqrt{(Z\,Y)} = \beta + j\alpha$ with $\alpha = \beta$.

Resolving $\cosh a\tau$ and $\sinh a\tau$ into their real and imaginary components, we have

$$\cosh a\tau = m + jn = \cosh\beta\tau \cos\beta\tau + j \sinh\beta\tau \sin\beta\tau.$$

$$\sinh a\tau = p + jq = \sinh\beta\tau \cos\beta\tau + j \cosh\beta\tau \sin\beta\tau.$$

Substituting these in Equation (7) we have P = the real part of

$$i_2^2 \beta\rho (1+j) \left\{ (k - m - jn) \left(\frac{km + jkn - 1}{p + jq}\right) + kp + jkq \right\}$$

Therefore

$$P = i_2^2 \beta\rho \left\{ \frac{p+q}{p^2+q^2} (k^2 m + m + k n^2 - k m^2 - k) - \frac{p-q}{p+q} (k^2 n + n - 2 k m n) + k(p-q) \right\}$$

$$= i_2^2 \beta\rho \, F(\beta\tau, k)$$

where $F(\beta\tau, k)$ signifies that function of $\beta\tau$ and k within the brackets. This function has been calculated for a number of values both of $\beta\tau$ and of k and the values are tabulated in Table 5.

Table 5.

Values of $F(\beta\tau, k)$.

$\beta\tau$	$n = 2$ $k = 2$	$n = 3$ $k = 1{\cdot}5$	$n = 4$ $k = 1{\cdot}33$
0·5	2·093	0·566	0·283
1·0	1·727	0·753	0·551
1·5	2·780	1·626	1·343
2·0	4·18	2·652	2·262
2·5	5·081	4·77	—
3·0	5·36	3·51	3·02

* *Journal I.E.E.*, 1916, vol. 54, p. 474.

Discussion.

Professor C. L. Fortescue: The first part of the paper, namely that dealing with a straight wire, is really the method given by Lord Rayleigh and Lord Kelvin, but explained in a very ingenious way. For students, or for engineers who have studied the transmission of power along definite lines at moderately high frequencies, the idea of the power transmission into the conductor is, I think, extremely valuable; but for others who perhaps have not thought so much about that, I am not sure that the same results cannot be obtained more simply by considering the eddy currents and that the same graphical method cannot be applied. It would be of interest to know if the author has considered whether one cannot derive the results from simply a straightforward

consideration of the eddy currents in the conductors. Passing on to the coils, which I consider to be really the important part of the paper, there are two very serious difficulties which the author has indicated more or less clearly. There is the distribution of the magnetic fields between the individual conductors. That is an extremely difficult problem, and the way in which the product S_7 enters into so many of the equations, and the fact that S_7 has to be estimated in the first case, indicates, I think, quite clearly the extreme difficulty of allowing for the lines between the turns of the wire. The second difficulty is that due to the main flux—the main magnetic field produced by the current in all the turns. It will be observed that except just at the end the author has calculated his formulæ for long solenoids. Those results are very valuable, but unfortunately the short solenoid is the important practical case, and it becomes a question how far the method of correction the author has suggested actually works out in practice. I have tried one or two points, comparing the results given in the paper with the results obtained from curves in which allowance is made for the end effects of the coils, and I find that for coils in which the diameter is roughly the same as the length the author's method of correction works quite well. It really comes to this :— The author still assumes the same distribution of lines even for the short coil, but he reduces the flux on the inside and calculates on that basis. Actually the lines are dividing and bending round. How the correction will work if it comes to a case of a pancake coil in which the diameter may be 10 times the length, I do not know. It presents a very difficult problem indeed. To pass on to the question of the use of stranded wire ; both in the Royal Society paper and in the extracts which the author has given, it is rather implied, I think, that stranded wire has no very great practical application. Curves were prepared which have been available for the use of a considerable number of people in the course of the last 5 years, and when properly used I think that stranded wire is thoroughly justified. It means, of course, a great deal of extra work. To make all the connections is extremely difficult. Moreover, if one takes a stranded wire of perhaps over 1,000 single parts, the production of a few thousand yards of this wire means a few million yards of the fine wire. That makes it very expensive. But there is no doubt that wherever overall dimensions present any difficulty at all the stranded wire is really the only solution. If one takes high-power continuous-wave transmission above perhaps 1,000 metres, unless one is prepared to go in for coils of the order of 8 or 10 feet in diameter and an axial length of perhaps 4 or 5 feet, the stranded wire is essential and, of course, the multiple-layer coil is also essential. Dimension for dimension, given the same volume, the stranded wire will nearly always give a lower resistance than a solid wire, or a single-layer coil. I have worked out one simple case to illustrate that point, and I have intentionally chosen a coil in regard to which I suppose nine designers out of ten would not even think of putting in stranded wire. I have taken a single-layer coil 6 inches long and 6 inches in diameter with 48 turns. That gives a coil of about 220 micro-henries inductance, such as might be used for a small valve transmitter, for example, over a range of from about 600 to 1,000 metres. No. 14 S.W.G. solid wire giving a considerable amount of spacing provides about the lowest resistance. It is between 1·1 and 1·2 ohms. If one completely fills the space—a No. 11 S.W.G. solid wire will just about do so—the resistance is slightly larger, about 5 or 10 per cent. With a stranded wire made up of 81 wires of No. 38 S.W.G., the resistance decreases to from 0·8 to 0·9 ohm. That is a 30 per cent decrease in the resistance, which means possibly a 20 per cent increase in the radiation from the aerial and is all to the good. So that even in this case where one would ordinarily use a solid wire, the stranded wire has really a very marked advantage, and when one comes to multiple-layer coils it becomes practically essential. Perhaps one of the outstanding points of the paper is the practical impossibility of calculating these resistances accurately. This has been very much impressed on the minds of all who have been endeavouring to calculate these resistances, and for accurate work it seems essential to depend on practical measurement. At the present time I believe the National Physical Laboratory are endeavouring to measure the resistance of coils quite accurately. I do not know what method they have in view, but I think the thermal method used by the author is really the only reliable one. A calorimeter method is the only one that can be relied on, because it is the only method which measures the heat generated. If one uses bridge methods or resonant methods, where one has to adjust to a peak value of the current, to halve the current, and so on, one is never quite sure that one has really got those peak values. That particularly applies to the case of coils which have a very low power factor—where one is working with less than 1 ohm per 1,000 micro-henries. That is the kind of coil that it becomes very important to measure, and getting down to these very low power factors, by any resonant or bridge method is equivalent to trying to weigh milligrammes with a 2 or 3 lb. weight on each side of the scale. The author has given curves of his own results in Figs. 10 and 11 in which the calculated results are rather higher than the observed ones. He says nothing of any correction for the capacity of the coils. If that correction were appreciable, it would possibly bring the dotted lines on to the calculated lines and make the results even better than he has assumed.* One notices that Esau's figures fit in quite well with the calculations, and it would be rather interesting to know what the method of measurement was—whether it was the bridge or the resonant or the thermal method. In conclusion, I do not know whether the author has attempted to measure the resistance losses in a condenser by the same method. It is an extremely important point. In many cases the resistance of a condenser is assumed to be nil, but in practice even a good air condenser, owing to insulation losses and so on, may have a loss equivalent to 4 or 5 ohms.

Mr. P. R. Coursey: I should like to make a few remarks about the subject of high-frequency resistance, more from the practical point of view than from the mathematical side that is dealt with in this paper.

* *Communicated* : This is incorrect. As stated by Mr. Coursey, the capacity correction is in the opposite direction and makes the difference between the observed and calculated results greater instead of less.

Professor Fortescue has just mentioned the self-capacity correction for the resistance of the coil, but it seems to me that that correction is in the opposite direction to what he says. I think Lindemann's formula for this correction comes down to this, using the notation of the paper:—

$$R_c' = \frac{R_c}{(1-\omega^2 C_0 L_0)^2}$$

where R_c' = the measured effective resistance of the coil,
R_c = the true effective resistance,
$\omega = 2\pi \times$ frequency,
C_0 = self-capacity of the coil,
L_0 = inductance of the coil.

The effect of this correction is surely to make the experimental values higher than the calculated ones. In that case it would tend to depress the full-line curves in Figs. 10 and 11 in the paper, instead of to raise them. As a point of interest in connection with the correction for the length of the coil as given by the author, I have worked out a few examples with the help of his formulæ, in order to compare them with some experimental measurements that I happen to have on hand. Some of them are as follows:—

Coil Diameter (Inches)	Coil Length / Diameter	Wave-length (Metres)	Experimentally Measured R_c'/R	R_c/R, corrected for C_0, from R_c'/R	R_c/R, calculated from Formulæ in Paper
3	0·905	760	7·6	6·5	4·9
3	0·905	1,000	5·85	5·32	4·27
3	0·905	1,400	4·72	4·50	3·61
4	1·175	1,400	3·36	2·80	2·80
4	1·175	1,980	2·47	2·26	2·31
4	1·175	2,420	2·34	2·21	2·10
5	1·015	2,420	1·63	1·19	1·50
5	1·015	3,600	1·26	1·11	1·25
5	1·015	4,850	1·18	1·10	1·15

It is perhaps interesting to note that the tendency seems to be that the greater the wave-length the more nearly do the calculated and experimental values come into agreement The experimental ratios become lower than the calculated ones for the larger wave-lengths, whereas they are higher for the smaller ones. The table also illustrates the magnitude of the self-capacity correction mentioned above, and shows that in most cases it brings the two sets of values of R_c/R_0 more nearly into agreement. These measurements were made with a deflectional method by adding resistance to the circuit and noting the decrease in current. This is very much quicker than the calorimeter method, although this and all such similar arrangements give the resistance of the entire high-frequency circuit, instead of just the coil resistance. Allowances must therefore be made in the readings for the effective resistance of the remainder of the circuit (including the condenser) at the frequency used. It should, however, be mentioned in connection with the calorimeter method, that it necessitates the use of much larger currents than the coils are often required to carry when in normal use. This may involve a considerable extra loss in the dielectric surrounding the wire, particularly if the wire is covered with cotton or anything of that nature. Even with air insulation, if the voltage on the coil is high (as when carrying a large current), there may be some loss due to brushing. Such a loss is known to be appreciable in some forms of air condensers, and it is possible that it may also have some effect even with air-insulated coils, and particularly with multi-layer ones.

Mr. H. W. Taylor: On page 152 of the paper the author says: "In the ordinary telephone transmission the energy is propagated through a medium of air or guttapercha: here, however, the energy is propagated through copper." I think that this statement can with advantage be made more general as follows: "In any form of transmission the energy is propagated both outside and inside the conductor by virtue of the fluxes which whirl both outside and inside the substance of the conductor: in the case of the fluxes which whirl inside the conductor, some of the energy is dissipated because of the comparatively good electrical resistance of the conductor: in the normal case the fluxes outside the conductor do not give rise to a dissipation of energy, but when the conductor is surrounded either partly or wholly by a conducting medium, then in this case energy is also dissipated outside the conductor." In the study of all eddy-current problems it is very important to recognize the distinction between the two cases just mentioned, and as an illustration I would refer to the problem of the high-frequency resistance of a multi-layer coil considered by the author. This problem is very closely allied to the problem of the eddy-current losses in conductors retained in alternator slots. It can be shown by simple physical reasoning that the impedance factor of the bottom conductor, which corresponds to the outside layer of a coil, may be expressed in the form of a complex hyperbolic cotangent as follows:—

$$\beta\tau(1+j)\coth\beta\tau(1+j)$$

while the impedance factor of conductors higher in the slot corresponding to the inner layers of a coil, may be expressed by an additional term in the form of a complex hyperbolic tangent as follows:

$$2(n^2-n)\beta\tau(1+j)\tanh\beta\tau(1+j),$$

this term arising from the fact that the inner layers form a conducting medium in the field of the outer layers. When the average loss factor of a number of conductors or layers is required, the coefficient $2(n^2-n)$ in the last expression must be replaced by $\frac{2}{3}(n^2-1)$. All the symbols in the above expression are as used by the author. The real and imaginary portions of the above functions may be readily found in terms of ordinary hyperbolic and circular sines and cosines, the real portion being the resistance factors and the imaginary portion the reactance factors in terms of direct-current resistance. The real portion of the first expression has already been plotted by the author in Fig. 6, but for the convenience of reference, all the curves relating to both functions are plotted in Fig. A herewith. These curves may be readily used to calculate the resistance of a coil

with any number of layers, and all the figures given in Table 3 have been checked in this way and the missing figures in the fifth line have been found to be 63·7 and 28·1. It should be understood of course that these and also the author's formulæ apply only when the inside and outside radii of the coil are comparable. When the inside of the coil is small compared with the outside, as in a pancake coil, the coefficients $2(n^2-n)$ and $\frac{2}{3}(n^2-1)$ must be replaced for exact calculation by elliptic functions, and when the inside and outside radii of the conductor itself are not comparable with one another, the complex hyperbolic functions must be replaced by complex Bessel functions. On page 159 the author discusses the losses in multi-layer coils with reference to the number of layers. Such a problem usually takes the form of filling a space already decided upon for other reasons with a coil of copper in such a way that the loss may be a minimum. The space may be filled in many ways, of which the two indicated in Figs. B and C are possible extremes. As long as the value of $\beta\tau$ for the individual strips in Fig. C is small, this arrangement is better, but it must not be overlooked that if $\beta\tau$ of the individual conductor is larger than, say, 1 to 1·15, depending upon the number of conductors, less loss will result by reducing the section of the conductor (as in Fig. D) and increasing the apparent current density. With regard to the formulæ in the first column on page 153, I think the constant term of 0·25 is unnecessary. The formula given by the author for the equivalent depth of penetration applies to flat strips only, and for round wires a correction has to be made, as the author himself seems to indicate later on page 154. He says "The same result would be caused by a decrease in the permeability and either would lead to an increased penetration." That is, the curvature of the surface of the conductor leads to slightly increased penetration. I think if he makes a correction for this in his derivation of the formula he will find that the 0·25 will disappear, leaving the formulæ as Lord Rayleigh originally gave it. I should like to suggest that the formulæ near the bottom

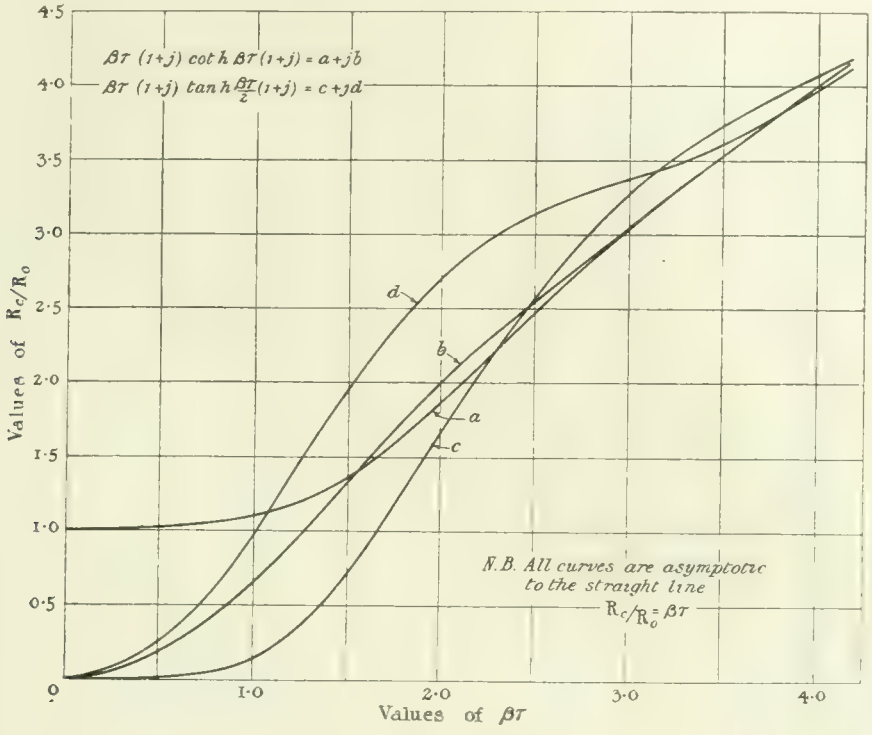


FIG. A.

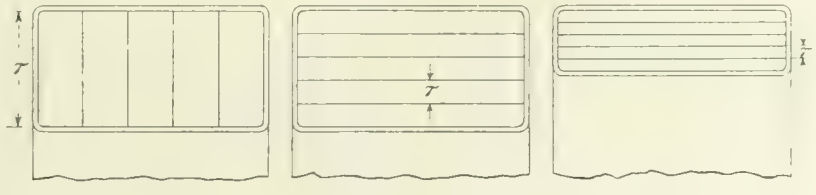


FIG. B. FIG. C. FIG. D.

of the first column of page 154 of the paper, might be put in a more convenient form, thus:

$$\frac{R_f}{R_o} = 1 + \frac{4}{45}(\beta r)^4$$

and that it may be safely used for values of βr up to 1·1. Similarly, the corresponding approximate form for the loss factor of round wires is $\frac{R_f}{R_o} = 1 + \frac{(\beta d)^4}{768}$, where R is the radius of the conductor in centimetres, and this formula may be safely used for values of βd up to 3·8. This approximate formula for small round wires supplements the approximate formula given by the author for large round wires. They were both originally given by Lord Rayleigh (*Philosophical Magazine*, Ser. 5, 1886, vol. 21, p. 387).

Mr. F. Murphy: I am afraid that many of these formulæ are so laborious that one is practically forced to adopt some form of measurement. In addition to that, each designer has certain physical considerations

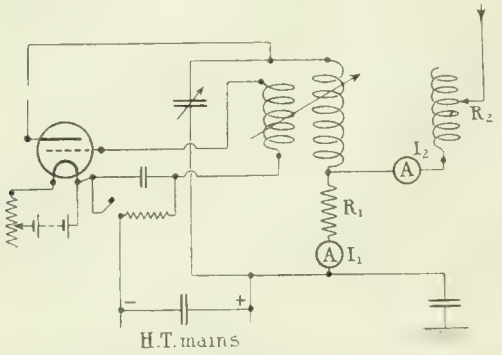


FIG E.—Diagram of connections for measurement of effective resistance of oscillatory circuits at radio frequencies.

to which he has to conform, and he cannot take the simple cases which are given in the paper and work on those. For example, in the case of aeroplanes, we have to squeeze our loading coil into the smallest possible space, and we cannot use a straightforward single-layer coil. Referring to Fig. 12, the author quotes a case of a multi-layer coil of square wire. I should like his opinion as to the relative high-frequency resistance of a single-layer coil of square wire as compared with a flat spiral square wire of the same mean diameter; that is, if we imagine in Fig. 12 the inner and outer layers omitted and a corresponding spiral made up with the square wire on edge. Another point I should like to raise in connection with high-frequency resistance is the effect of the dielectric losses. In making up small coils where space is an essential factor, one is forced to use some dielectric other than air between the turns. Take a case of braided strip coil; we undoubtedly get in a transmitter the dielectric subjected to a fairly considerable high-frequency voltage, and it would seem that the dielectric loss must be a fairly considerable factor in the total high-frequency resistance. Fig. E shows a diagram of connections of a method which I have found very suitable and convenient for measuring high-frequency resistances. It consists essentially of an oscillating valve, and included in the inductance portion of the anode circuit is a non-reactive resistance and a hot-wire ammeter. Across that hot-wire ammeter and non-reactive resistance is either an aerial circuit or the inductance coil to be measured with an air condenser in series to which the anode circuit is tuned. Since the oscillatory circuit under test is, as a whole, non-reactive, the current in the ammeter A_2, multiplied by the high-frequency resistance of this circuit, gives us the voltage across the non-reactive resistance and the ammeter A_1. Hence all that is necessary to do is to take the values of the two ammeter readings, and knowing the value of the non-reactive resistance in the anode circuit, we obtain the high-frequency resistance by multiplying the non-reactive resistance by the inverse ratio of the two ammeter readings. The value of the method lies in its simplicity. It is quite possible to take, say, a curve connecting the high-frequency resistance of an aerial with the wave-length over quite a fair range in half an hour. In addition

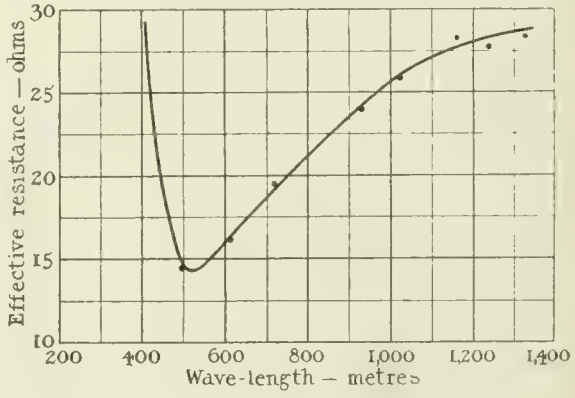


FIG. F.—Effective resistance of single-wire aerial system.

to that it is a method which is quite applicable to take into the air, and this is scarcely true of any of the other methods. Fig. F shows a curve which was taken of an ordinary single-wire aerial. The points lie fairly well on the curve, which seems to point to the fact that the method is fairly accurate. As a check on the method for measuring the high-frequency resistance of coils I tried the effect of adding to the oscillatory circuit under test a non-reactive resistance of a known value, and again measuring its resistance by this method. The known value of the non-reactive resistance was 14 ohms, and checking it by this method it came out at 13·5, which seems fairly reasonable, as the ammeters available for the test were not of the first order of accuracy.

Mr. R. C. Clinker: The author has a way of presenting these problems which appeals to those who are not strong on the mathematical side, and which makes the subject most attractive. There is one question I should like to ask him with regard to the first column on page 158 where he describes the tests made. Is it possible in such a method that any inaccuracy might be introduced owing to the heating of the coil through which the high-frequency current is passing

being not necessarily uniform? That is to say, the direction of the flux not being parallel to the axis of the coil near the ends might produce more heating in some of the turns than in others; whereas, when one passes a direct current through it one gets uniform heating throughout the coil. I notice the temperature was measured at the centre of the coil. That does not, of course, give the mean temperature throughout the coil.

Dr. W. H. Eccles: The author has been very modest about the amount of new information given in the paper, but I appreciate that some of these curves, like Figs. 9, 10 and 11, for example, are very considerable contributions to our knowledge. The points that I might refer to in a critical spirit are as follows: To begin with, there is the author's treatment of the multiple-layer coils. Usually one builds a multiple-layer coil to make an inductance of a stated amount, and one needs a much smaller length of wire if one makes the coils in layers rather than in a single-layer solenoid. I would ask the author if he has taken that into account in comparing the losses in coils designed for the same work. Then, again, as regards stranded wire, I know that the author has long urged that stranded wire is of little advantage; but other people are equally emphatic that it is indispensable. I must say I am just as unsettled as ever after reading this paper and after Professor Fortescue's comments. I think we must still keep an open mind as regards which is the better in the various problems that arise in practice. But, of course, the "nigger in the woodpile" in both the calculation and the measurement of high-frequency resistance is the capacity between the turns and the body capacity of a coil to its surroundings. Take a coil and measure it at different wave-lengths approaching its natural wave-length. We may do this by passing current through it and through measuring instruments in series. When at its natural wave-length there is a big voltage between its terminals and practically no current flowing into it, and yet if we measure the current at the middle we find a high value. Some observers have measured the current at the middle, and others at the ends, and they have obtained very different results. This is true whether the measurement is made by an ammeter or by the substitution of resistances in series with the coil, as I think Mr. Coursey has done. I think I know of papers which claim to show that the resistance of a coil increases to infinity at its natural wave-length. It is all on account of disregarding the effects of distributed capacity. That is what really surprises me in some of Sommerfeld's work. Take Fig. 9; Sommerfeld himself, and Professor Howe following him, have quite freely extrapolated to infinity. The curves say that at a certain frequency the coil's resistance would be so-and-so; but at that frequency there would be nodes and loops upon it, which would alter the distribution of the energy absorption and would make the resistance different. Various modes of correcting for the effect are available but are difficult in application. Therefore much depends, in criticizing any particular experimental results, on the method of measurement and correction adopted by the investigator, and it is wise never to trust anything fully until one has had an opportunity of seeing exactly what the investigator did. Unfortunately, when the investigator does not realize fully the importance of this matter, he does not give us enough data. I know of several cases where, on inquiring in regard to the method the author used, one finds he has left out something absolutely necessary for the critical examination of his method. Finally, I must refer briefly to another effect of the capacity of the windings, namely, the distortion of the current stream lines in the skin of the metal. This appears to have been neglected by most writers on the subject; nearly all writers assume that the magnetic flux moves without regard to the motion of the lines of electric force, and this is probably not justifiable at very high frequencies.

Mr. J. Hollingworth (*communicated*): The author has here tackled a problem of great complexity. All who attempt to deal with the mathematical side of wireless telegraphy are at once confronted with the problem that it is absolutely necessary to make assumptions in order to reduce the analysis to a workable amount, and it is very difficult to tell without experimental verification whether the factors neglected may not prove to be the vital ones determining the result. Fig. 9 is very interesting, though, as often happens, in data collected from various sources the results of each observer tend to form a group by themselves and so make comparison more difficult. Broadly speaking, however, the experimental values of R_c/R_f seem to come greater than the calculated ones. Is it possible that this is due to the capacity between the various turns of the coil, not necessarily adjacent ones? Of course, if the coil under test is not part of a tuned circuit, the voltage between turns will be small, but of the energy radiated outwards from any individual turn a certain proportion, depending on the value of $S\,d$, will be re-absorbed by other turns. Also the current distribution will be affected, and the geometrical centre of the coil where the thermo-couple was placed may cease to be the mean position electrically. This effect will be very much magnified when higher harmonics are present in the wave-form, not only due to the fact that owing to their higher frequency they will pass more freely through such capacities, but also due to the dangers of local resonance. It would be interesting to know the effect of the damping on high-frequency resistance. The results quoted are partially spark and partially continuous oscillations. Experience in the reception of continuous oscillations seems to point to the fact that a much higher resistance is possible than when receiving damped waves. I have in an extreme case connected the filament of a 200-volt 16-c.p. carbon lamp into a closed coil receiving circuit without causing a very great reduction in the continuous-wave signal strength. This effect may, of course, be involved with the theory of optimum heterodyne reception about which not much is known at present. Under these conditions, however, a spark station was rendered practically inaudible. I am inclined to think that in certain cases reception by means of triode valves is actually improved by a certain amount of resistance in the oscillating circuit. Such sets are generally worked near to the regenerating

point, even on spark reception, in order to give good amplification. They have in consequence somewhat of a tendency to be unstable, which is reduced by resistance in the receiving circuit, and it does not seem safe to assume in such cases a direct relation between high-frequency resistance and efficiency. It is surprising to note how the general tendency of investigators is to depose multiple stranded wires from the position they once held.

Mr. W. L. McPherson (*communicated*): In this paper we see all too clearly the difficulties which surround the design of radio apparatus. Exact experimental data are rare, and empirical and workable formulæ for the calculation of coil resistance at high frequencies are unknown. In certain cases, which do not occur in practice, the resistance may be calculated by pure mathematics with comparative ease; for practical cases, however, the mathematics are such that few engineers will feel at home with them, and the resulting formulæ are so complex as to be totally unmanageable unless simplified by judicious assumptions and approximations. A debt of gratitude is due to the author for this paper, in which he gives us reasonably simple formulæ that can be applied with fair accuracy to practical design. It is rather a pity that he has not dealt with flat spiral coils, now in such common use, and I am sure that a paper from him on this subject would be welcome. The experimental figures quoted by the author were obtained with the aid of a Poulsen arc as a source of power. In all probability a valve generator would be more suitable, as the harmonics are much less prominent, and the frequency so steady that a tuning condenser could be profitably employed in the secondary circuit, reducing the power necessary to drive a given current through the coil. For the rapid measurement of high-frequency resistance we have found the "inserted resistance" method quite reliable, giving results correct to within approximately 5 per cent. It calls for a careful disposition of the circuit, however, as otherwise capacity-to-earth effects cause a considerable amount of trouble. But I must agree with a previous speaker that it is not suitable for the measurement of very low-resistance coils. Though not specifically dealt with in the paper, the dielectric used as former, and the insulation of the wire itself, play an important part in the high-frequency resistance of a coil. Cotton covering especially has proved bad, even for receiving coils which are subject to no great potential; this is probably due to the absorption of moisture by the cotton. The fact that abnormal self-capacity in such a coil is accompanied by an increase in the high-frequency resistance would appear to confirm the above. With regard to the employment of multiply stranded wire, it has certainly proved of little use on very short wave-lengths. In one particular case, at a wave-length of 50 metres the high-frequency resistance of a coil wound with stranded wire was found to be between 40 and 50 times its steady current resistance. On longer wave-lengths, however, especially with multi-layer coils, its advantages appear in practice to outweigh its disadvantages. This is particularly the case with lap-wound coils. We have had no trouble with such coils when wound with stranded wire, but in several cases in which solid wire was used the high-frequency resistance could only be described as terrific.

Captain B. E. G. Mittell (*communicated*): With regard to the question of the value of divided wire, Mr. C. F. Elwell tells me that the 931 silk-covered strands of No. 27 copper wire at the Lyons station have successfully carried over 200 amperes of high-frequency current in continuous service. He attributes importance to the fact that one never obtains copper commercially of the same grade as is used in theoretical work, and that pure copper is more nearly obtained when buying divided wire. Another point is, that he uses a special method to force the current into every wire.

Mr. L. B. Turner (*communicated*): The resistance of inductance coils is a subject with which the designer of wireless apparatus is necessarily intimately concerned. It is a subject which in the past has suffered in two opposite ways: the over-empirical school has wholly disregarded the theory on account of the diversity, complexity, and uncertainty of the formulæ developed; while the over-theoretical school has put its trust in the incomplete and unverified "Litzendraht" doctrine, adopting finely stranded wires regardless of cost and manufacturing difficulties, in the mistaken belief that some large if indefinite gain in efficiency was being obtained. A mere Wheatstone bridge test of finely stranded inductance coils will often show that a considerable proportion of the strands are broken or defectively soldered (especially in the case of enamelled strands); and, as the author has pointed out, even with perfect workmanship the high-frequency resistance may often considerably exceed that of a solid winding of the same overall dimensions. The paper provides a much-felt want, and should be of especial value to the designer as presenting him with checked results in readily computable form. The introduction of the continuous-wave transmitter and of the retro-active triode receiver has great and diverse significance for the subject of this paper. On the one hand, whereas with the damping inseparable from the old spark transmitters no sensible advantage could accrue from extreme reduction of decrement in the other circuits—a fact which has been sometimes overlooked—in accurately tuned circuits receiving a sustained and truly isochronous oscillation, every reduction in decrement brings its proportional gain. Hence a new importance is attached to low decrements; and simultaneously the oscillating triode has conveniently transformed the laboratory measurement of high-frequency resistance into an easy and accurate operation. But, on the other hand, whereas extremely low receiver decrements are now required, the use of retro-action in the receiving circuits gives us a ready means of reducing the effective resistance by any desired amount, whatever be the intrinsic resistance of the inductance coils employed. Receiving inductances of low intrinsic resistance are therefore, in fact, not necessary. The need for low-resistance transmitting inductance coils, however, remains.

Professor G. W. O. Howe (*in reply, communicated*): It is not claimed that the method and formulæ developed in the paper are applicable with mathematical accuracy to any coils met with in practice. They merely represent

an attempt to establish on sound scientific lines working formulæ which may serve as a basis for the correlation of experimental data and assist the designer of high-frequency apparatus in the determination of the losses to be expected in his coils. As Professor Fortescue rightly remarks, the method is the classical and only method, but regarded from a new point of view. So far as I am aware, the graphical method of treating skin-effect problems was first employed by Professor Hay in 1910; he did not use the transmission-line idea, but the two methods are really identical. The method which I have suggested for the correction to be applied in the case of short coils is, of course, a very crude approximation, but, as Professor Fortescue remarks, it works very well. The many other assumptions and approximations which have to be made do not justify the complications which would follow any attempt to go more accurately into the correction for coil length. I quite agree with Professor Fortescue that there are many cases in which stranded wire gives a lower resistance than solid wire. In my Royal Society paper I give tables showing the relative values and it will be seen that in many cases the stranded wire has a considerable advantage. This advantage is, however, very much less than was generally thought and is associated with very serious disadvantages. The method employed by Esau in the experiments referred to by Professor Fortescue was an alternating-current bridge method. I have not attempted to measure the losses in a condenser by the calorimeter method, but I believe that it has been done.

Both Professor Fortescue and Mr. Coursey refer to the effect of self-capacity on the distribution of current along the coil. No correction for this was made in the results recorded in the paper because, as will be shown, the effect was negligible. At frequencies approaching the natural frequency of the coil a considerable error may be made if this effect be overlooked, and this undoubtedly accounts for some of the discrepancies between the results obtained by other experimenters and plotted in Fig. 9. The action of the capacity between the ends of the coil in shunting some of the current has the effect of increasing the current through the coil. This, at first sight, paradoxical result is due to the fact that the capacity current is 180° out of phase from the current through the coil. If the self-capacity be regarded as concentrated in a condenser joined across the ends of the coil the currents through the coil, condenser, and external ammeter will be respectively

$$\frac{V}{\omega L_o}, \quad V\omega C_o, \quad \text{and} \quad V\left(\frac{1}{\omega L_o} - \omega C_o\right)$$

Hence, using Mr. Coursey's nomenclature, the power lost as heat in the coil will be expressed as

$$V^2\left(\frac{1}{\omega L_o} - \omega C_o\right)^2 R_c'$$

when it should be expressed as $\frac{V^2}{\omega^2 L_o^2} R_c$. Hence

$$R_c = R_c'(1 - \omega^2 L_o C_o)^2$$

which is the formula referred to by Mr. Coursey as Lindemann's correction formula. If ω_o be the natural frequency of the coil alone, $\omega_o^2 = 1/L_o C_o$ and

$$R_c = R_c'(1 - \omega^2/\omega_o^2)^2$$

Now the coil employed in the experiments recorded on page 158 and in Fig. 10 has a total length of wire of 7·5 metres, a natural wave-length of about 10 metres, and a natural frequency of 30 millions. Even at a frequency of a million, $\omega/\omega_o = 1/30$ and

$$R_c = R_c'\left(1 - \frac{1}{900}\right)^2 = \frac{449}{450} R_c'$$

A very similar result will be found for the coil of Fig. 11. This sufficiently explains why the effect was not taken into account. The current distribution along the coil was very uniform and, as the coil was of bare wire resting on a small glass rod, there is little possibility of secondary losses. Brush discharge between the turns is out of the question, since with a current of 1 ampere and a frequency of 1 million the electromotive force is about 2 volts per turn.

As Mr. Taylor states, the loss in any layer of a multi-layer coil can be expressed as the sum of two losses, one due to the uniform field produced by the other layers and one due to the magnetic field produced by the layer considered. Both these component losses can be found very simply in the way he suggests, but it was thought that the method adopted in the paper formed a direct and interesting application of the transmission-line conception. Mr. Taylor is quite wrong, however, in thinking that the constant 0·25 is superfluous in the formulæ in the first column of the second page of the paper. Lord Rayleigh's form of this equation is only approximately true when the first term is so great that the 0·25 becomes negligible. It is always more accurate with the 0·25 term. For values of x greater than 8·5, where $x = \beta d$, the value of R_f/R_o in terms of Bessel functions may be written

$$\frac{R_f}{R_o} = \frac{x}{4} + \frac{1}{4} + \frac{3}{16x}$$

with an accuracy of one part in a thousand. The second term in this expression is the one which Mr. Taylor thinks superfluous. It was pointed out in the paper that the graphical method of determining the value of R_f/R_o for a straight wire when applied to the case for which $d\sqrt{f} = 79$ gave a value 3·035, whereas the formula which Mr. Taylor criticizes gives 3·28. This discrepancy gave some appearance of probability to Mr. Taylor's contention that the formula was correct without the term 0·25. Since the paper was read, however, one of my students has carried out the graphical construction with the radius divided into 20 sections, which gave $R_f/R_o = 3·19$, and then with 40 sections, which gave $R_f/R_o = 3·26$. Hence the discrepancy was due entirely to the inaccuracy involved in dividing the radius into only 10 sections.

Although the method described by Mr. Murphy may be very simple, it contains too many possibilities of error to make it a suitable method for very accurate calibration purposes. Apart from the necessity for

accurate tuning there is the uncertainty as to the equivalent resistance of the remainder of the circuit, especially of the condenser. In determining the effective resistance of an aerial this latter difficulty does not arise.

Considerable thought had been given to the unequal heating of the coil due to the end effects mentioned by Mr. Clinker, but I came to the conclusion that any error due to this effect would be very small.

In reply to Dr. Eccles's criticism it should be pointed out that the results given for multi-layer coils are not intended in any way to disparage these coils, but merely to enable the designer to determine the resistance of such a coil from the resistance of a single-layer coil, with which he may be assumed to be more familiar. The determination of the best type of coil to use in any given set of conditions is obviously a problem outside the limits of the present paper. When the frequency is so high or the coil so long that the current distribution along the coil is far from uniform, the value of I^2 to be used in calculating I^2R is not that at the end nor at the middle, but the mean value of I^2 taken along the coil. From this point of view one is justified in extrapolating the values of R_c/R_0 far beyond the natural frequency of the coil.

Mr. Hollingworth raises the point of the difference in the effective resistance when using damped waves. Although it has been shown that the resistance for the same frequency and effective current is greater with damped than with undamped waves, the difference is very small with moderate damping. Some of the results given in Figs. 10 and 11 were obtained with a quenched spark-gap and were found to lie on the same curve as those obtained with the arc.

I quite agree with Mr. McPherson that a thermionic valve would have proved a more satisfactory source of power than the Poulsen arc, but the experiments described were made four to five years ago, when the thermionic generator was almost unknown.

With regard to the points raised by Captain Mittell, I find it very difficult to believe that any appreciable difference in the high-frequency resistance can be due to the alleged greater purity of the smaller wires. I see no reason why 931 silk-covered strands of No. 27 wire should not carry 200 amperes of high-frequency current. Assuming a space factor of 0·5 and a pitch equal to twice the diameter of the conductor, the value of R_c/R_0 at a wave-length of 15,000 metres would be about 5·25. R_c is therefore 10·5 times the direct-current resistance of the solid wire which could be used in place of the stranded conductor. With $\lambda = 15{,}000$, the resistance of this solid wire coil would be 16 times its direct-current resistance. Hence the losses are reduced in the ratio $10{\cdot}5/16$ by using the stranded conductor. As pointed out by Mr. Elwell, it is essential to take proper precautions at the terminals to ensure that the current is equally distributed between the wires.

ELECTRICITY IN TIN MINING.

By D. M. W. Hutchison, B.Sc., Member, and W. J. Wayte, Associate Member.

(*Paper first received 6 June, and in final form 24 November, 1919; read before* The Institution *in December, 1919.*)

Introduction.

The object of this paper is to create a greater interest in the problem of the application of electrical power to tin mining.

The paper is divided into the following parts, viz.—

Part I.—A general review of the tin position in the Federated Malay States and the methods of mining in vogue.

Part II.—Detailed descriptions of four typical electrical mining plants using different methods.

Part III.—Recommendations in regard to machinery in the Federated Malay States in particular.

Appendix.—Mathematical formulæ and tests.

PART I.

General.

The full title of this paper should be "Electricity in Tin Mining in the Federated Malay States," the authors' experience not having extended beyond the tin fields of that country; methods of mining are, however, generally similar in other parts of the world.

The group of States, Perak, Selangor, Negri Sembilan and Pahang, known as the Federated Malay States, or the F.M.S. for short, and which form part of the Malay Peninsula, furnish the product known in the metal market as "Straits tin"; the output is very large, the exports in 1913, the last normal year, being 50,127 tons of metal, value approximately £9,800,000.

The labour force employed in tin mining in the same year numbered 225,000, 216,000 of this number being Chinese, but the adoption of machinery and other causes combined has resulted in recent years in a large decrease in the number employed.

Machinery, which is already used to a large extent, is likely to come into use much more in the near future. The present position roughly is that European-owned mines employ a maximum of machinery and a minimum of labour, and the Chinese-owned mines a maximum of labour and a minimum of machinery. There are of course exceptions, some Chinese owners having installed up-to-date electric plants.

Mines under Chinese management in 1918 produced about 70 per cent of the total output, and as there are less than half a dozen electrically-driven Chinese mining plants there should be great scope for the electrical engineer in the immediate future.

In 1917, 7,600 kilowatts of generating plant and 8,300 horse-power of motors were installed on tin mines, but the majority of mines where power is employed still use steam, generally in a very wasteful fashion.

The increase in the cost of firewood owing to its scarcity, the discovery in recent years of a valuable deposit of coal in Selangor suitable for burning on mechanical grates, and the necessity that now exists for working low-grade propositions on a large scale, are three factors which are bound in the near future to result in the installation of up-to-date economical power plants for mine working.

The labour used for mining purposes is almost entirely Chinese: the ordinary Chinese coolie is a born miner, and appears to be naturally gifted with the instinct to locate tin-bearing ground.

Up to the present time very little methodical prospecting work has been done by Chinese miners. The large mines are usually started by small parties of tributers who appear to decide upon the right spot to commence operation either by guesswork or by instinct: the Chinaman is a gambler and faces his losses philosophically.

The pre-war rate of pay for Chinese labour was 60 cents (1s. 5d.) a day; it is now about 80 cents (1s. 10½d.).

Mechanics are usually Chinese, but there is a fair sprinkling of Tamils, Bengalis, Japanese and other races, the pay varying from $1.40 to $2 per day (3s. 3d. to 4s. 8d.).

Men in charge of electrical machinery have by law to possess certificates of competency issued by the Examining Board under the Electricity Enactment. This law extends to European engineers, who, however, if Associate Members of this Institution, are not called upon to appear before the Board.

The rate of pay varies greatly with the individual, especially in the higher grades, but the following are approximate rates paid in Perak:—

2nd grade chargemen $24 per month (£2 6s. 11d.).

1st grade chargemen $40 to $75 (£4 13s. 9d. to £8 15s. 8d.).

2nd grade engineer $120 to $200 (£13 11s. 2d. to £23 8s. 8d.).

1st grade engineer $350 to $450 (£39 to £50 14s. 7d.).

The authors think it advisable at this point to consider as briefly as possible the problem to be faced by the miner in working alluvial tin deposits.

The ore-bearing ground, or karang, lies in beds, varying in thickness from a few feet up to 20 feet or more, which may be close to the surface or may be as far below the surface as 150 feet, a depth of 70 feet being more usual. In some cases the karang is found in one or more large beds; in others it may be found

TABLE I.

Open Cast Mines.

NAME OF MINE	YEAR	POWER HOUSE: Prime Movers	POWER HOUSE: Total kw and Gen. Volts	POWER HOUSE: System, voltage	POWER HOUSE: Annual Output in Units	DISTRIBUTION: Winches No.	Winches b.h.p.	Puddlers No.	Puddlers b.h.p.	Gravel Pump No.	Gravel Pump b.h.p.	Water Pump No.	Water Pump b.h.p.	Other Uses No.	Other Uses b.h.p.	Total No.	Total b.h.p.	COST PER UNIT GENERATED† Fuel	Oil and Stores	Repairs and Maintenance	Salaries and Wages	Total Works Cost	VARIOUS DATA: Fuel Used and Cost (delivered)	Fuel per Unit	Units Used per Cubic Yard	Power Cost per Cub. Yard, cents	Cubic Yards Treated	REMARKS
Sungei Best	1917	Steam compound condensing	525 kw 550 v. 3 ph. 50 ~	500 v. M. 230 v. d c for L.	1,044,000	Steam		1	80	1	50	2	500	6	107	10	737	2·00		0·45		2·45*	Rawang coal $4·03 per ton	0·1 lb.	7·9	19·5	205,631	Lb. of fuel per unit in 1919 reduced to 6. Installing mechanical stokers and economizers
Lahat Mines	1918	Diesel	220 kw. 2,200 v. 3 ph. 50 ~	2,200 v. and 400 v. M. 230 v. L.	1,695,104 purchased	4	120	Gas		2	120	2	355	4	82	12	677	—	Power purchased from Pengkalen			—		—	3·7	—	425,021	Diesel stand-by only
Tekka Mine	1918-19	Diesel	136 kw. 650 v 3 ph. 50 ~	650 v. M. 230 v L.	9 months 415,500	2	40	2	60	—	—	3	150			6	250	1·47	0·16	0·04	0·84	2·51*	Crude oil 22 C. per gall.	0·076 gall.	2·8	7·45	140,000	Distribution costs 0·20 cent per unit. Tekka and Tongwon supervised by same engineer
Tongwoh	1918-19	Diesel	272 kw. 650 v. 3 ph. 50 ~	650 v. M 230 v. L	9 months 556 500	2	36	2	59	—	—	3	180	—		7	275	1·33	0·11	0·01	0·78	2·23*	Crude oil 20 C per gall	0·066 gall	3·0	7·16	173,309	Distribution costs 0·36 cent per unit. Auxiliary, steam

* Includes cost of distribution of mine. † In cents

Abbreviations: C = Cents. (To convert cents to pence multiply by 0·28) L = Lighting. M = Motors

in several beds at varying depths, and in many cases there are no well-defined beds, the whole of the ground containing tin ore to some extent.

The object of the miner is to get the ore out of this karang with the least possible expenditure, and he has, roughly speaking, a choice of three methods:—

(I) Open cast mining.
(II) Hydraulic.
(III) Bucket dredging.

As each of these methods presents a different problem in regard to the supply and utilization of power, it has been considered most convenient to deal with them in turn. It does not follow, however, that every mine adopts one of these methods only; this is by no means the case.

The problem of lode mining is treated separately, as no useful comparison can be made between this form of mining and alluvial mining. At present only a very small proportion of the total tin output is won in lode mines, but as alluvial deposits become worked out more attention will no doubt be devoted to this form of mining.

(I) Open Cast Mining.

A typical large open cast mine in full working consists of one or more huge oblong pits in the ground, perhaps 80 feet deep and many acres in extent. At one end of each pit will be an incline consisting of a double line of rails up which the karang is hauled to the puddler station; in another position a similar incline for the removal of overburden, which is dumped out of the way, into an old working for preference.

The puddler station, which usually serves one pit only, consists of a level timber platform forming a terminus to the karang incline, and is furnished with rails and a double-drum winch which serves to haul up the full trucks and lower the empty ones.

The full trucks are brought to rest on the puddler platform opposite an opening directly over the puddlers into which the karang is tipped.

The puddlers are of two main types, that used depending on the class of ground worked or on individual fancy. The most widely used type is merely a cylindrical open top brick or iron tank about 25 feet in diameter with a wood block floor, in the centre of which is a vertical shaft driven at about 5 revolutions per minute by bevel gearing. This shaft carries four cross-arms, to the ends of which are attached two cast-iron "harrows" fitted with blunt teeth. The karang being dumped into this machine and mixed with water is churned by the harrows The process is continuous, the mixture after being churned being led to sluice boxes through a coarse screen.

The other type of puddler consists of a horizontal shaft carrying knives and running in a plated timber container at a speed of about 120 revs. per minute. This high-speed type is generally furnished with a flywheel to take up shocks when the karang is tipped in.

The puddled mixture, in either case, is led by launders to the sluice boxes after being thinned down slightly by the addition of clean water. The sluice box, which forms a common feature in all tin-mining systems, consists of two or three compartments 200 feet or so long, furnished with removable slats across the bottom which catch the heavier tin particles and allow the lighter sand and slimes to escape to the tailings dump. Each compartment is capable of dealing with the whole output of the puddler serving it, and this allows the others to be washed down with clean water and the tin ore removed without any slackening in mining operations.

Open cast mines are of all sizes, varying from the modest hole in the ground worked entirely by Chinese labour to propositions with capitals of £120,000 or more.

In nearly all mines of this type, however, power is used in some form or other. The source of power in most general use is the portable non-condensing steam engine burning wood fuel, and it is quite common to see half a dozen or more of these fuel-wasters at work on the same mine. It is only fair to state, however, that for outputs of from 60 to 100 horse-power very efficient, portable, condensing, superheated steam engines can be obtained.

Diesel and hot bulb engines are in use to a certain extent, and in some of the large mines and in several smaller ones electricity is the driving power.

The chief uses for power are for hauling, pumping (both for unwatering the mine and for supplying water for the puddlers and sluice boxes), and for puddler driving and lighting the mine at night.

Table 1 gives particulars of four typical open cast mines, and Tables 2 and 3 of hydraulic-electric, dredge and lode mines. In all cases (except Lahat, Pengkalen and Idris) the energy used has been calculated from switchboard readings, and a power factor of 0·75 to 0·8 has been assumed. Mine managers who indulge in the practice of buying plant direct from the manufacturers would do well to insist on a proper provision of instruments for measuring the output. If, as is usual, they ask for tenders for "one plant complete," they should not expect luxuries and certainly will not get them.

It has been impossible in many cases to separate generation from distribution costs, but when possible this has been done. This must be borne in mind when comparisons are made with hypothetical bulk-supply systems. Capital costs have been omitted owing to the general practice of grouping together generating and mining plant; such figures as are obtainable are apt to be misleading.

It will be seen that some mines are run partly by electricity and partly by steam or gas, the two latter being used as a rule for operating the fluctuating winch or puddler loads or as a stand-by for emergency pumping in case of flooding. Naturally such a practice produces a high electrical plant load factor, but when electrical plant can be obtained again the whole of the mining load will doubtless be dealt with electrically, with a benefit to the all-round power costs.

The question of generating on a large scale in central stations and distributing to mines has been discussed many times, most recently by a Commission appointed

TABLE 2.

Hydraulic-electric Mines.

NAME OF MINE	YEAR	POWER HOUSE: Prime Movers	POWER HOUSE: Total Kw. and Generated Volts	POWER HOUSE: System, volts	POWER HOUSE: Annual Output in Units	DISTRIBUTION: Winches No.	Winches b.h.p.	Water Pumps No.	Water Pumps b.h.p.	Gravel Pumps No.	Gravel Pumps b.h.p.	Nozzle Pumps No.	Nozzle Pumps b.h.p.	Other Uses No.	Other Uses b.h.p.	Total No.	Total b.h.p.	COST PER UNIT GENERATED, CENTS: Fuel	Oil and Stores	Repairs and Maintenance	Salaries and Wages	Total Works Cost	VARIOUS DATA: Fuel used and Cost	Fuel per Unit	Units used per Cubic Yard	Power Cost per Yard Treated	Cubic Yards Treated	Static Head at Power House, feet	Static Head at Mine, feet	Length Pressure Pipe above Power House, miles	Length Pressure Pipe below Power House miles	Length Trans. Line, miles	REMARKS
French Kampar	1917	2 Water turbines	744 kw. 6 600 v. 3 ph. 50 ~	Step down 400 v M. 110 v. L.	2,327,234 (*a*)	—	—	—	—	3	370	2	150	—	202	—	722	—	—	—	—	1·76* (*b*)	Crude oil	—	5·72	11·02 C	383,500	1,312	—	—	—	1	1917 output includes powe sold to tributers used for town lightin
	1918	1 Diesel			1,757,000	—	—	—	—	4	435	2	150	—	—	5	595	—	—	—	—	—	17·17 C per gall		6·25	13·26 C	238,500	—	—	—	—	—	(*a*) Diesel 1,059 140
French Tekka	1918	Pelton wheels	1,020 kw. 450 v. 3 ph. 40 ~	Step up 6,000 v., step down 400 v M. 230 v. L	4 760,000	3	69	10	144	8	859	—	—	2	16	23	1,088	—	(*c*)	0·12	0·83	1·01*	—	—	3·14	3·84 C	1,270,000	328	328	2	4·35	7	(*b*) Overall cost for est mated total output (*c*) Not included
Idris Hydraulic	1918–19	Pelton wheels	900 kw. 400 v. 3 ph. 50 ~	Step up 3,000 v., step down 400 v. M. 230 v. L.	6 months 900,890	—	—	1	35	6	510	—	—	—	—	7	545	—	—	0·11	0·37 (*d*)	0·48	—	—	—	—	—	936	360	1	1¼	1·5	(*d*) Exclusive of cost Head Office supe vision
Pengkalen	1917–18	Steam turbine and triple expan. engine	1 100 kw. 2 200 v. 3 ph. 50 ~	Step down 400 v M. 230 v. L.	4 208,800	4	120	6	400	4	371	1	110	6	182	21	1,173	1·68	0·03	0·06	0·42	2·17	Local coal $6·86 per ton	5·5 lb	—	—	—	—	—	—	—	5	Started as suction dredg Shut down Nov. 191 Now sells powe Water-tube boile chain grate stoke overhead power line

* Includes cost of distribution on mines.

Abbreviations: C = Cents. (To convert cents to pence multiply by 0·28.) L = Lighting. M = motors..

to inquire into various questions connected with tin mining.

The authors do not consider that the prospects of a power company would be very rosy, for the following reasons :—

(1) Absence of diversity. Beyond a very small proportion of town lighting there is practically only the mining load to consider.

(2) Limited paying life of the power company due to tin-bearing areas being worked out. It must be remembered in this connection that the application of power to mines now mainly worked by coolie labour would result in the deposits being more rapidly exhausted.

(3) Heavy capital charges due to the high rate of interest expected in this country and also due to heavy amortization charges on account of short life.

(4) Comparatively poor load factor during useful life, due to the short-lived nature of many mines, the temporary shutting down or restriction of output in times of low tin prices, and the failure to get the most profitable consumers—the large mines, which can generate very cheaply with their own plants. The majority of a power company's consumers would be the small or medium-sized Chinese mines now using portable engines and working from 10 to 18 hours out of the 24.

(5) Heavy wayleave and maintenance charges, as the lines running over mining land would have to be moved frequently.

A co-operative power station to supply a group of well-proved mines is of course a different proposition altogether and seems to be the solution of the problem. There is no reason why such a power station could not supply the more or less ephemeral demands of small mines nearby in addition to its nucleus load.

The authors do not consider, taking everything into account, that the average yearly load factor of a power company taken on the maximum useful station capacity over the period of its paying life would exceed 40 per cent. A co-operative group power station under similar circumstances should be able to reckon on a load factor of 50 to 60 per cent. In this connection it is as well to bear in mind that the years now under review were years when the tin output was being forced up as much as possible to provide munitions, and plants were being run to their greatest capacity.

At present, steam users with a certain maximum horse-power installed have a way of overestimating the horse-power-hours used per annum, with the result that the calculated cost per horse-power-hour comes out unduly low and unfavourable comparisons are made with electricity. A comparison of units generated and brake horse-power connected on electrically-worked mines will give a good idea of what may be expected in this way.

(II) Hydraulic Mining.

Hydraulic mining may be defined as a process whereby the ground is removed and treated by the agency of water. It has many forms and combinations falling into three main classes :—

(1) Hydraulic mining proper, including ground sluicing.
(2) Hydraulic-electric mining.
(3) Suction dredging.

Hydraulic mining proper.—Here the ground is cut by jets of water projected by monitors under a natural head of from 50 to 400 feet, and the mixture, if necessary, elevated by hydraulic elevators (see Fig. 1) to the sluice boxes where the treatment follows the procedure outlined under open cast mining. In ground sluicing,

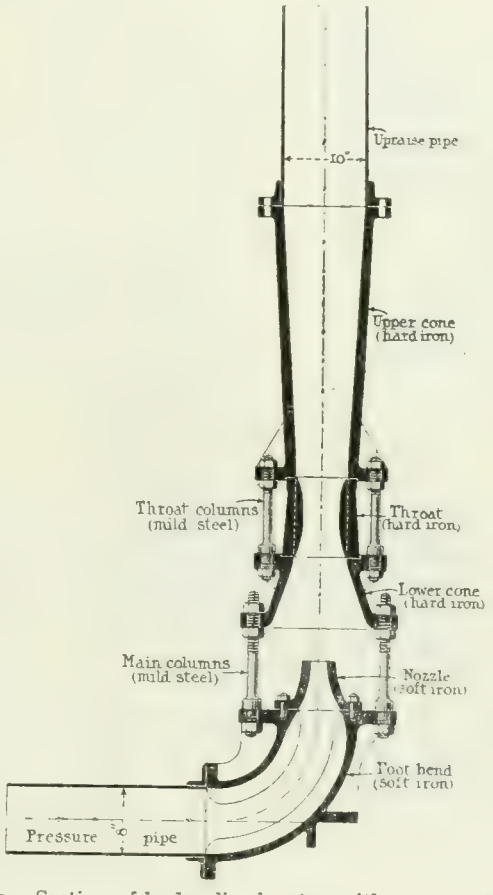


Fig. 1.—Section of hydraulic elevator, with names of parts.

which is usually carried out on only a small scale, the ground is broken down by hand labour into channels where it is mingled with water, the resulting mixture being passed over sluice boxes.

Overburden and karang are generally treated in the same way, although in some cases the overburden is removed by coolie labour. The hydraulic method, using water under pressure, is used on some of the largest properties in the country, and provided that plenty of water at a suitable elevation is available, and that the value of the property is sufficient to justify the cost of an expensive dam and pipe line, this method is usually adopted.

Hydraulic-electric mining.—Where economy in the use of water is necessary, or where the ratio of head

to lift is less than about 5 to 1, making the economical use of elevators out of the question, or where the total head would be unnecessarily high for the monitors, it is usual to install gravel pumps and to use part of the available head for generating electricity to drive these pumps, the remainder being used for the monitors.

The gravel pump is a centrifugal pump of special make (see Fig. 2) provided with renewable liner and wearing plates, capable of raising any stone which can enter its open-ended suction pipe. Its efficiency is naturally not high and figures for performance are

Other tests and records are given in the Tables, and as an average the efficiency of pump and pipe work may be taken at about 38 per cent, as against 16·6 per cent for the elevator.

Suction dredging.—A suction dredge consists of a centrifugal pump to supply a monitor jet, together with a gravel pump to elevate the mixture, the whole being mounted in some cases on a pontoon together with the necessary boilers and engines or, if electrically driven, motors. This pontoon usually rests on dry land, but is moved about to fresh places in the mine

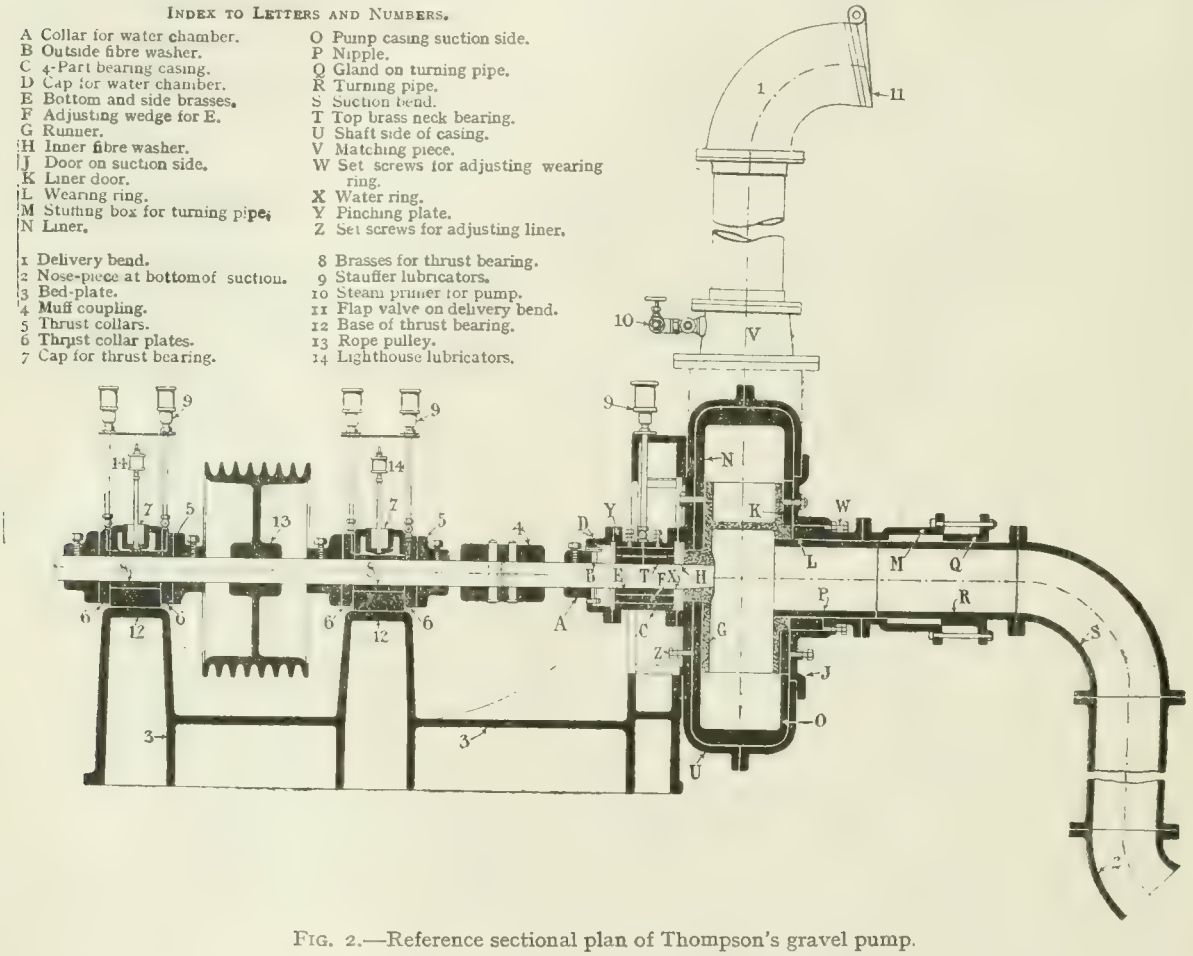

INDEX TO LETTERS AND NUMBERS.
A Collar for water chamber.
B Outside fibre washer.
C 4-Part bearing casing.
D Cap for water chamber.
E Bottom and side brasses.
F Adjusting wedge for E.
G Runner.
H Inner fibre washer.
J Door on suction side.
K Liner door.
L Wearing ring.
M Stuffing box for turning pipe.
N Liner.
O Pump casing suction side.
P Nipple.
Q Gland on turning pipe.
R Turning pipe.
S Suction bend.
T Top brass neck bearing.
U Shaft side of casing.
V Matching piece.
W Set screws for adjusting wearing ring.
X Water ring.
Y Pinching plate.
Z Set screws for adjusting liner.
1 Delivery bend.
2 Nose-piece at bottomof suction.
3 Bed-plate.
4 Muff coupling.
5 Thrust collars.
6 Thrust collar plates.
7 Cap for thrust bearing.
8 Brasses for thrust bearing.
9 Stauffer lubricators.
10 Steam primer for pump.
11 Flap valve on delivery bend.
12 Base of thrust bearing.
13 Rope pulley.
14 Lighthouse lubricators.

FIG. 2.—Reference sectional plan of Thompson's gravel pump.

hard to obtain, but Mr. J. J. Garrard in a paper read before the Institution of Mining and Metallurgy in February 1917 gave an average annual efficiency of 27·25 per cent for a gravel pumping installation. As electrical losses were included, the combined efficiency of pump and motor works out at about 42 per cent, the mixture pumped being about 5 per cent solid by bulk. The figures of a well-known maker of these pumps are given in Fig. 3, and show an efficiency of 50 per cent for the pumps under similar conditions or, including the motor, say 42·5 per cent, which agrees very well with Mr. Garrard's result.

As against this the efficiency of an elevator is given in Mr. Garrard's paper as 16·58 per cent.

by floating it off. Many mines prefer to mount their pumps in a permanent position on concrete foundations, but the process is just the same and is, for convenience, called suction dredging in this paper. The essential difference between this and other forms of hydraulic mining is the use of pumps both for producing pressure at the monitor and for elevating the mixture.

Fig. 4 gives particulars of the performance of one type of nozzle pump used. It must be remembered that the water pumped is generally the effluent from the tailings dump, with perhaps a certain amount of clean seepage water mixed with it, so that a strong construction is more to be desired than a high efficiency pump, which would quickly be rendered useless by the

TABLE 3.

Miscellaneous Mines.

Name of Mine	Year	Power House: Prime Movers	Power House: Total kw. and Gen. Volts	Power House: System Voltage	Power House: Annual Output in Units	Distribution: Motors No.	Distribution: Motors b.h.p.	Cost per Unit Generated in Cents: Fuel	Oil and Stores	Repairs and Maintenance	Salaries and Wages	Total	Various Data: Fuel used	Units used per Cubic Yard or Ton treated	Power Cost per Yard or Ton, Cents	Cubic Yards or Tons treated	Remarks
Tin Bentgon Dredge	1918	Pelton wheel	800 kw. 2,200 v. 3 ph. 60 ∾	Step up 11,000 v., step down 2,200 v. and 230 v M. 110 v. L.	1,403,500	10	680	—	—	0·37	0·80	1·17		1·69 per cub. yd	2·21	775,500 cub. yd	Motors on dredge 595 b.h.p. Motors on shore 85 b.h.p.
Chendai Lode	1916–17	Power purchased		400 v. M 230 v. L 3-ph. 50 ∾	6 months 85,470	3	120	—	—	—	—	—		19·80 per ton		4,355 tons	Motors—Ore crusher 10 b.h.p. Stamps 75 b.h.p. Tables and mills 35 b.h.p.
Pahang Consolidated Lode	—	Steam turbines and Diesels	950 kw. 550 v. 3 ph. 50 ∾	500 v.	3,350,000 approx.	—	1,000	—	—	—	—	—	Wood and Crude Oil	—	—	—	Compressor motor 435 b.h.p. Pumps 565 b.h.p underground Boiler supply steam winders in addition Mill driven by Diesels

L = Lighting. M = Motors To convert cents to pence multiply by 0·28.

TABLE 4.

French Mine Kampar 1917 *and* 1918.

Year	Mine	Gravel Pumps: Average Work done: Lift, ft.	Water c. ft. per Min.	Gravel c. ft. per Min	Hours run: No. I	No. II	Average for Pumps I and II: Units per Hour	Efficiency, %	Tailings Pumps: Average Work done: Lift, ft.	Water c. ft. per Min	Tailings c. ft. per Min.	Hours run: No. III	No. IV	Average for Pumps III and IV: Units per Hour	Efficiency, per cent	Nozzle Pumps: Average Work done: Lift, ft.	Kinetic Pressure Head, ft.	Water c. ft. per Min.	Hours run: No. V	No. VI	Average for Pumps V and VI: Units per Hour	Efficiency, per cent	Cost Data, Etc.: Working Costs at Mine in Cents: Power per Unit	Power per cub. yd.	Total per cub. yd.	Cubic Yards moved	Plant Data
17	No. 2	78	234	11·05	7,702	—	86	37·7	-	-	—	—	—	- -	-		80	202	- - 62	- -	35	70·5	2·0	0·07	27·30	189,000	10-in gravel pump 48 r.p.m. 145 b.h.p. motor direct drive. Monitor pump 950 r.p.m. 75 b.h.p. motor direct drive
17	No. 3	78	234	11·06	7,892		110*	38·7*	24	234	11·06	7,892	—	-	- -		80	202	7,892		40·27	66·5	1·90	13·70	30·42	194,000	10-in. gravel pump 480 r.p.m. 145 b.h.p. motor direct drive. Monitor pump 950 r.p.m. 75 b.h.p. motor direct drive 8-in. tailings pump 360 r.p.m. 80 b.h.p. motor direct drive
n to June, 1918 ..	No. 3	81	234	11·4	2,920	—	80	42·4	24	234	11·4	2,920	—	33	30·4	—	60	202	2,920	—	38·9	51·5	2·12	13·26	34·05	74,000	
ly to Dec., 1918 ...	No. 3	81	2·4	12·0	3,5·0	2,610	80·6	42·2	41	234	12·0	3,500	2,610	48·7	35·3		60	211·5	3,500	2,610	40·6	51·7	2·12	13·26	34·05	164,500	2 10-in. gravel pumps 480 r.p.m. 145 b.h.p. motor direct drive 2 monitor pumps 950 r.p.m. 75 b.h.p. motor direct drive. 11-in tailings pump 360 r.p.m. 80 b.h.p. motor direct drive 18-in. tailings pump 475 r.p.m. 75 b.h.p. belt drive

Efficiency averages: Gravel and tailings pumps 37·8 %. Nozzle pumps 61·55 %. Motor efficiency is assumed to be 85 % in all cases.

* Units per hour for one gravel and one tailings pump and efficiency average for the two pumps.

grit in the water. Some figures for nozzle-pump performance will be found in Fig. 4.

Hydraulic Electric Systems Analysed.

Where the hydraulic-electric system is contemplated there is a choice of methods, which have been treated

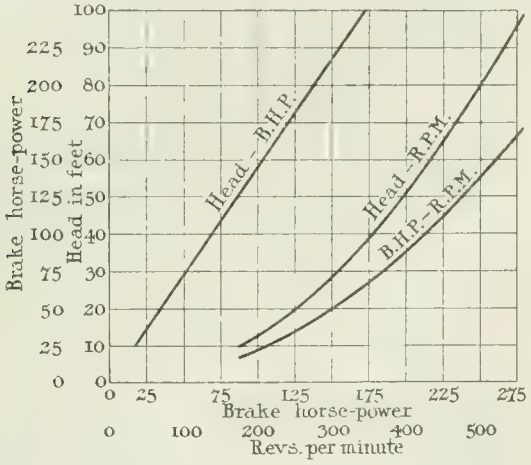


Fig. 3.—Makers' figures for 10-in. gravel pump lifting 50 cub. yards of solid per hour.

mathematically in the Appendix under hydraulic-electric mining.

System 1: Ground Sluicing and Gravel Pumping.

This method is occasionally used where there is a plentiful supply of labour and the necessary water close to the mine. The power for driving the gravel pumps need not necessarily be generated by falling water, but a comparison has been made in the Appendix which shows that, given a certain water power, 28 per cent more work can be done by employing the water power to generate electricity to drive gravel pumps than by using it for elevators.

The brake horse-power required to drive gravel pumps can be obtained roughly from Fig. 3, or can be calculated from the formula in the Appendix. The usual mixture is about 5 to 7 per cent. The makers of these pumps rate them at so many cubic yards of gravel lifted per hour, but this method of rating pumps is crude and it would be far more satisfactory to rate them in their capacity in gallons of water per hour, considering that about 90 per cent at least of the mixture raised consists of water.

The pump works with a shallow open sump and a suction life of 15 feet or so as a rule, and delicate speed regulation is necessary to keep the water level in the sump constant.

It must be remembered in this and all other alluvial tin-mining practice that in very few cases can pumps be installed to suit their best performance and be kept at work in that position. As the mine develops, the pumps must be moved and conditions as to head and discharge are continually varying.

What then is required is a motor that is capable of a large variation of speed together with fine regulation at any speed, and these conditions are in theory best fulfilled by direct-current motors coupled direct to the pumps.

As, however, three-phase current is generally used owing to convenience in distribution it is the usual practice to drive the pumps direct or by belt by induction motors and to regulate the speed by rotor resistances. In some cases the motors are run at full speed and throttling pieces put in the delivery pipe, which has the effect of introducing artificial head, thus cutting down the delivery.

Both these methods are of course wasteful, but it is probable that they will continue in use in preference to the use of direct current.

There are two or three small direct-current pumping plants which have given good results, but there is very unlikely to be any great extension in its use as in the future there will be a tendency towards group

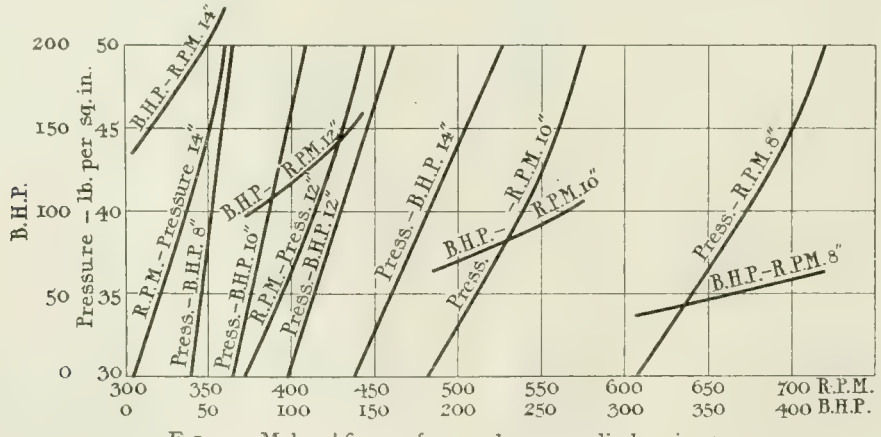


Fig. 4.—Makers' figures for nozzle pumps discharging:

8 in. 160 cub. ft. per min.
10 in. 280 ,, ,,
12 in. 430 ,, ,,
14 in. 624 ,, ,,

stations, thus involving three-phase working. In any case, however, where there is a possibility of installing a small compact plant close to the mine the advantages of direct current for most mining operations, especially pumping and hauling, would outweigh the disadvantages due to the slightly greater complication of brush gear and commutator.

Variable-speed direct-current motors are in use in a colliery in the Federated Malay States under fairly severe conditions, and there is no climatic reason why they should not be used where it would be good policy to do so.

System 2: Divided-volume System.

Here the cutting is done by jets of water under natural head directed on to the working face by monitors, the size of the jet being usually about 2 inches diameter.

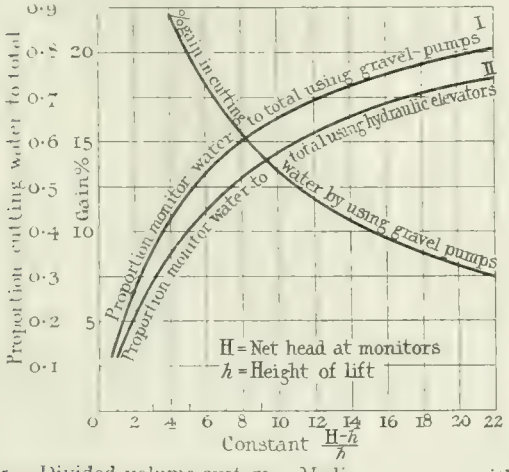

Proportion cutting water to total
Gain %
Constant $\frac{H-h}{h}$
% gain in cutting to total using gravel-pumps
I
II
total using hydraulic elevators
Proportion monitor water to total water by using gravel pumps
Proportion monitor water
H = Net head at monitors
h = Height of lift

FIG. 5.—Divided-volume system. Medium pressure without transformers.

The whole of the available pressure water is piped to the mine and there utilized, partly to supply monitors and partly to generate electricity for the purpose of driving gravel pumps to elevate the mixture cut by monitors.

The proportion of water available for cutting, after allowance has been made for lifting, has been worked out mathematically in the Appendix, and curve I of Fig. 5 gives the results for various values of the constant $(H-h)\div h$ when the allowance for seepage is 10 per cent of the monitor water and the mixture cut contains 7 per cent of solids.

The value $(H-h)/h$ varies in practice between 4 and 7 except when starting a mine, when it may be much larger for a short time owing to the value of h being small.

Curve II has been plotted for comparison and gives the amount of water available for cutting if hydraulic elevators are employed instead of gravel pumps. Elevator and hydro-electric cum-gravel-pump efficiencies have been taken at 16·6 and 23 per cent respectively throughout, and although this assumption of constant efficiency over the whole of the curves may not be justifiable, the error over the portion of the curves which are of practical value, i.e. between values of 4 and 7 for $(H-h)/h$, is not likely to be large.

It will be seen that the extra amount of water available for cutting, and consequently the extra ground cut by substituting gravel pumps for elevators, is considerable, being as much as 22·5 per cent for a value of $(H-h)/h$ of 4.

The question of gravel pump versus hydraulic elevator may not depend on efficiency alone: where waste of water is unimportant the hydraulic elevator will score owing to its low capital and maintenance costs. There are, however, certain advantages in the use of gravel pumps which may weigh heavily; for instance, if the ratio of height of lift to head is too low it becomes necessary to elevate in two lifts, and this is such a wasteful operation for hydraulic elevators that it is practically out of the question except on a small scale for working small pockets.

The gravel pump is capable of a maximum lift of about 100 feet although it loses efficiency, except in the largest sizes, at lifts much over 70 feet; but pumping in two lifts by gravel pumps, where necessary, is hardly less efficient than pumping in one, whereas to use elevators in two lifts is an exceedingly inefficient process as the higher elevator has to take not only the monitor water but the lower elevator pressure water as well, so that the proportion of the elevator to monitor water may be about $2\frac{1}{2}$ to 1 and the efficiency of the process, even under favourable conditions, about 9 per cent.

System 3: Divided-head System.

In many cases the water available for working the mine has to be piped long distances from a comparatively high elevation. It is found in practice that in most classes of ground worked there is no economy in using pressures higher than about 200 lb.; in fact, most hydraulicing is done at pressures considerably less. Where the pressure is too high the ground is cut away too quickly and the resulting mixture of ground and water has to be thinned down by the addition of more water to a consistency which will flow towards the sump and will not block the pumps. This extra water is supplied in most cases from the monitors; consequently the amount of ground cut may be said to vary with the quantity of water used irrespective of the pressure, provided the pressure is sufficient to break up the ground.

On this account it is the usual practice where a high fall is available to use the first part of the fall for generating electricity, which is transmitted to the mine for driving gravel pumps. The remainder of the fall is used for monitors, and as of course all the water which passes the Pelton wheels in the electric power station goes on to the monitors, this may be called the divided-head system.

A simple mathematical formula is worked out in the Appendix and gives the proportion in which the fall must be divided for average conditions, and the curves in Fig. 6 give the available monitor pressure for various heads and lifts on the assumption made before as regards consistency of mixture and seepage,

and assuming that all the water used in the power house is used again in the mine for cutting.

The curves show that, speaking generally, for the height of lift usual in practice (50 to 70 feet) heads of 600 feet and over are suitable for this system.

No comparison with the hydraulic elevator has been made in this case, as where the fall is high enough to suit the divided-head system it is too high to be economical for hydraulicing.

System 4: Suction Dredge System.

This has been discussed in the Appendix in the case where the motive power for driving the gravel and nozzle pump is derived from falling water.

A system involving the conversion of water power into electric power, which is again converted by the mechanical agency of a pump into water power for hydraulicing, naturally cannot compete in efficiency with the use of water power direct for the same purpose, except under extraordinary conditions, so

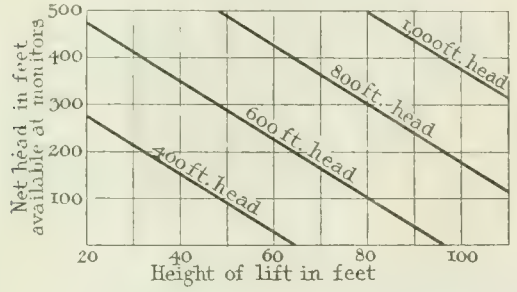


FIG. 6.—Divided-head system, showing head available for cutting with certain total net heads when using high-tension transmission with transformers for gravel pumps.

that this system is rarely used in conjunction with hydro-electric schemes. With very high heads, however, it may not always be convenient owing to the nature of the country, to use the divided-head system, in which case nozzle pumping is the only feasible alternative.

The suction dredge system has been used so far in this country chiefly in conjunction with steam plant, although the biggest installation of the kind at present in use derives its power partly from a hydro-electric and partly from a Diesel electric station.

Unless there is a large amount of seepage water which must be removed from the mine in any case, it is usual to pump the same water over and over again with a period for settling, the return water from the tailing dump being led to the suction side of the nozzle pumps and thus providing a certain proportion of natural head to the monitor.

(III) Bucket Dredging.

Bucket dredging is a form of alluvial mining which has become very popular in the Federated Malay States during the last few years, and will doubtless become more so, as the richer and more easily worked alluvial deposits become exhausted.

By this means, low-lying tin-bearing land of low grade can be worked at a profit which would not be practicable by any other method.

At the present time 17 dredges are operating in the F.M.S., only one of which is driven electrically, so that with a cheap supply of power tin dredging should open a wide field to the electrical engineer.

Land most suitable for bucket dredging is that met with in the neighbourhood of Taiping, where at the present time seven machines are operating all within a radius of 3 miles from Taiping. The tin-bearing ground is a gravelly wash, which is easily dug and treated, of an average depth of 45 feet below the surface. At this level a bed of hard clay is encountered which does not carry tin.

The Kinta Valley further south is a more difficult problem as the bottom is of irregular limestone, the pinnacles in some places rising to within a few feet of the surface and the depth varying to 70 feet or more. The best values are, moreover, usually on the limestone, so that the dredge and machinery must be of very robust construction to withstand the severe shocks which are of frequent occurrence.

PART II.

Hydraulic-Electric Mine near Kampar.

The most modern example of hydraulic-electric mining in the Federated Malay States is the Batu Karang mine of the Idris Hydraulic Tin Company, Ltd., which is situate 4½ miles from Kampar on the Kampar Gopeng Road, and is worked entirely by gravel pumps driven electrically, the power for generating current and cutting purposes being obtained from water on the "divided-head" system.

The pipe line to the power house is 81 chains long and is designed to carry 400 to 450 cubic feet of water per minute, the gross head being 955 feet and the effective head 935 feet. The diameter of the pipe varies from 21 inches to 16 inches.

The power station is built on a plateau on the hillside, the building being of steel covered with galvanized corrugated sheeting.

The plant installed is as follows:

Two Pelton wheels, each 700 b.h.p., 750 r.p.m., with governors of the oil-pressure type fitted with hydraulic automatic servo motors operating combined needle nozzles and deflectors. These drive through flexible couplings two alternators, each 450 kw., three-phase, 50 period, 400 volts, with the exciter overhung on an extension of the alternator shaft.

A bank of three single-phase transformers raises the pressure to 3,000 volts for transmission. The transformers are of the oil-cooled type, each of 187 k.v.a. capacity, and are connected delta-star, the neutral point of the generator being earthed through a resistance.

The transmission line is 1½ miles in length and consists of one circuit of No. 5 S.W.G. and one circuit of No. 7 S.W.G. bare copper wire carried on the same pole with an earth wire of No. 8 S.W.G. copper fastened to the top of the pole. The poles are of steel with cast-iron bases and buckled plates. The lightning

arresters at each end of the line are of the horn type with powdered carbon "Brazil" resistances. These arresters in conjunction with the earth wire have been found to give good protection against lightning.

The water after leaving the Pelton wheels is discharged into the intake of the lower pipe line outside the power station.

The pipe line is $1\frac{1}{2}$ miles in length, 16 inches in diameter, and a pressure of 170 lb. per square inch is obtained at the bottom of the mine where the water is used for cutting purposes with monitors.

The substation is placed close to the head of the sluice boxes and in the most favourable position for future work, and contains one bank of single-phase step-down oil-cooled transformers, each of 125 k.v.a. rating, 1,600/230 volts connected star-star, and one bank of single-phase transformers as above, but of 50 k.v.a. rating.

The neutral point of each group of transformers is earthed through a resistance.

The total height from the bed-rock to the sluice box varies from 70 to 90 feet, and a double-stage system of working is arranged as follows:—

Bottom lift.—The following pumps lift from the bottom of the lombong to the sump of the top lift, a total lift suction and delivery of from 35 to 45 feet.

One 8-inch gravel pump flexible coupled to an 80 b.h.p. motor running at 580 r.p.m.

Two 6-inch gravel pumps belt-driven by 65 b.h.p. motors running at 730 r.p.m.

Top lift.—The following pumps take their suction from the discharge of the lower lift pumps and deliver to the sluice boxes, the lift being 35 to 45 feet.

One 10-inch gravel pump flexibly coupled to a 140 b.h.p. motor running at 480 r.p.m.

One 8-inch gravel pump flexibly coupled to an 80 b.h.p. motor running at 580 r.p.m.

Tailings. The following pumps are installed to elevate the tailings at the end of the sluice boxes.

One 8-inch gravel pump flexibly coupled to an 80 b.h.p. 580 r.p.m. motor.

One 6-inch gravel pump belt-driven by a 65 b.p.h. 730 r.p.m. motor.

In addition, a 35 b.h.p. motor direct-coupled to a centrifugal pump raises water to the sluice boxes for ore-dressing purposes. The 8-inch and 10-inch gravel-pump motors are all provided with liquid controllers connected in the rotor circuit and capable of reducing the speed 50 per cent continuously if required.

Unfortunately no accurate records of power consumed and yardage are available, but approximate figures may be found in the tables.

The Idris Mine is equipped throughout with electrical machinery of British manufacture.

This is not the largest mine working on the divided-head system, French Tekka having this distinction. The latter has, however, been described before in the French technical Press.

Suction Dredge Plant on French Kampar Mine.

The Société des Mines d'Etain de Kinta own about 350 acres of tin-bearing land in Kampar, Perak, usually referred to locally as the French Kampar Mine.

At the present time most of the property is being worked on the suction dredge system. Power is generated in two stations, the original hydro-electric plant consisting of two horizontal radial outward-flow turbines working under the unusually high head for this class of machine of 1,312 feet. The generators are direct coupled through flexible couplings to 168-kw. three-phase alternators with overhung exciters running at 750 r.p.m. and generating current at 6,000 volts. The generator neutrals are all free.

The governing is by water pressure servo-motor actuated through the usual equilibrium valves by a governor driven off the generator shaft, the servo-motor altering the jet opening to suit the load by means of a shutter and a by-pass coming into action to prevent shock to the pipe when the jet is closing.

The switchgear calls for no special comment, being of the usual high-tension central-station type, and the generator switches being fitted with time-limit overload relays of the aluminium disc wind-up type.

The Diesel station, which is quite close to the hydro-electric plant and connected to it electrically by means of a three-core armoured cable, houses a 600 h.p. enclosed Diesel engine driving a 400 kw. alternator with revolving external magnet running at 250 r.p.m. A separate motor-driven compressor is installed in case of loss of air from the starting bottles.

The total capacity of the two plants in parallel is 744 kw., but for ordinary running the Diesel is looked upon as a stand-by to the water power which is apt to run short at times.

Kampar is a town situated at the foot of a large range of mountains, and it experiences lightning storms of remarkable severity, hence the lightning arrester gear deserves attention.

At the power-house end the gear is housed in a separate building and comprises horn-gaps and water leaks. The former have a break of 5 mm. and a resistance consisting of a column of alkaline electrolyte contained in two open-ended earthenware tubes provided with electrodes. The water leaks are of the enclosed type consisting of two glass tubes in parallel, 800 mm. long and 14 mm. internal diameter, connected between each phase and earth. A continuous circulation of water is maintained through the tubes. Flat choke coils are placed in the power house.

At the substations, horn-gaps with 7 mm. openings under cover with flat choke coils are installed on the high-tension side, the transformer neutrals being earthed on the secondary side.

This arrester gear gives good results except in heavy storms, when it is considered advisable to shut down. The probabilities are that the use of oil-cooled transformers at both ends of the line would, with the present arrester gear, enable the plant to run under all conditions.

The line consists of three No. 6 copper wires supported on porcelain insulators carried on 7 inch × 7 inch chengai poles spaced 115 feet apart.

The high-tension line feeds No. 3 mine substation and three small substations for town lighting which the company undertakes under agreement with the Government.

The present mine substation is a temporary wooden building with a floor of concrete, and has been designed to give ample space without being a very expensive erection. The high-tension line terminates on a pole outside and the wires are taken into the substation through a tower in which are placed the horn-gaps, choke-coils and high-tension switch. The transformers consist of a bank of one oil-cooled and three air-cooled (natural draught) three-phase core type, and the low-tension busbars are run overhead on insulators to the switchboards which control the circuits to the mine.

The low-tension neutrals are earthed and a tapping is taken at 110 volts for lighting in the mine.

For mining work where plant is always being moved about, nothing very elaborate in the way of substations is expected or required; the one described above is a good example. The usual point of danger which is apt to be overlooked is the entry of the high-tension wires; these are often brought down within 10 or 12 feet of the ground and then have to be fenced off in some way.

From the substation three circuits run to the gravel and nozzle pumps and mine lighting. All wiring is run overhead and bare for the most part, except within 7 feet of buildings where by a Government regulation it must be insulated.

There are two pumping stations.

Pumping station I.—This is the lower or first lift station, and houses two gravel and two nozzle pumps.

The gravel pumps are of the ordinary type in use in this country as illustrated in Fig. 2 with 10-inch outlets. At the time of writing this paper they were each engaged in lifting 234 cubic feet of water and 12 cubic yards of sand per minute with a suction head of 14 feet and a delivery of 67 feet.

The velocity in the delivery pipe is 7·5 feet per second.

Driving these pumps are direct-coupled 140 b.h.p. 480 r.p.m. slip-ring induction motors. Starting is effected by an oil-immersed rotor resistance, but no provision is made for speed regulation. During the early stages of development of the mine when heads were too low for the speed, overloading was prevented by the insertion of a diaphragm in the suction pipe.

The average length of run before a stop is made for adjustments is about 10 days, and liners have to be renewed about once a month.

The nozzle pumps are of the single impeller centrifugal type, with the suction side under a natural head of 50 feet, which is obtained by running back the clear effluent from the tailings dump. The pressure obtained at the pump outlet is about 110 feet with two $2\frac{1}{2}$-inch or $2\frac{3}{4}$-inch monitors running full bore, and regulation is effected by valves on the suction side.

All the main motors are controlled from a marble panel switchboard with a three-pole knife switch having cartridge fuses on each pole and an ammeter and voltmeter on each circuit.

Pumping station II.—The mixture of sand, tin ore and water raised by the pumps in the lower station passes over a sluice box 293 feet long with a fall of 11 feet, where the tin is deposited. The tailings are then raised by pumping station No. II to the dump.

This station contains one 10-inch and one 8-inch gravel pump with a suction head of 9 feet and delivery of 32 feet. The arrangement is similar to that in No. I as regards control.

Table 4 on page 177 gives the results of working for the years 1917 and 1918, and the costs and yardage may be taken as quite accurate. In regard to the volume of water pumped, this has been calculated from gauge readings on the monitor pump outlets and the area of the monitor jets, whilst the figures for the number of units used were taken from voltmeter and ammeter readings, assuming a power factor of 0·8, and were checked with the kilowatt readings in the power house.

The average efficiencies for gravel and nozzle pumps which have been worked out from the figures supplied may be safely taken as the results likely to be obtained by well-maintained pumps working under good conditions over long periods.

Lahat Mines, Limited.

This mine is situated about 5 miles south of Ipoh and is close to the Government road and the Ipoh-Tronoh Railway, and it is a good example of open cast working, the depth at the present time being 145 feet, but bores have been sunk to a depth of 250 feet from the surface and the bedrock has not been reached.

North Mine.—The karang is raised to the puddlers in truck up two inclines 600 feet long, each served by a 40 b.h.p. electric winch, a record of the number of trips being kept by mechanical counters and a recording ammeter.

The puddlers are four in number each 20 feet diameter running at 5 r.p.m. They are divided into groups of two, each pair being driven by a 15 b.h.p. motor through a double-reduction gear.

The water supply for the puddlers is provided by a 10-inch centrifugal pump driven by a 50 b.h.p. motor, 250 cubic feet of water per minute being required for this purpose.

The tin is recovered in a sluice box 160 feet long divided into three compartments each 5 feet wide. The yardage treated from the North Mine is approximately 16,000 cubic yards per month.

For removing the overburden from the western side of the mine two electric winches are installed driven by 20 b.h.p. motors.

Severe rain storms are experienced frequently, and to deal with seepage and rain water two turbo pumps are installed at the bottom of the mine each capable of dealing with 140,000 gallons of water per hour. The pumps run at 1,450 r.p.m. and are driven by 180 b.h.p. 2,000-volt induction motors.

South Mine.—This is a new extension, and is being opened up by a 6-inch gravel pump driven by a 40 b.h.p. motor.

The ground is broken down to the pump by two monitors fitted with $1\frac{3}{4}$-inch diameter nozzles, the pressure at the nozzle being 35 lb. per square inch, and the water being supplied by two centrifugal pumps driven by 20-b.h.p. motors. About 12 cubic yards

of solid per hour are elevated to the sluice boxes described previously.

Tailings.—The whole of the tailings from both mines are elevated to the tailings dump by an 8-inch gravel pump driven by an 80 b.h.p. motor.

Power plant.—Power is purchased from Pengkalen Limited, which is about $1\frac{1}{4}$ miles distant. The current is three-phase, 50 periods, 2,000 volts, and the transmission line is of bare hard drawn copper No. 1 S.W.G. carried on 6 inch × 6 inch hard wood poles.

A Diesel engine coupled to a 220 kw. generator was installed in a power station at Lahat Mines in 1914; this, however, is too small for the present requirements of the mine and is kept in reserve for emergencies. Further particulars of this mine will be found in the tables.

Tin Bentong Dredge.

The Tin Bentong No Liability Company own about 500 acres of mining land at Bentong, Pahang, which is being worked by an electrically-driven bucket dredge.

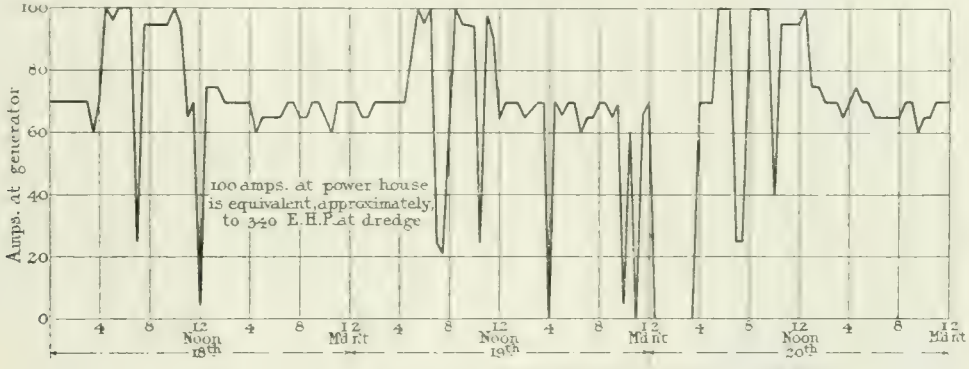


Fig. 7.—Load curve of power house, Tin Bentong dredge, 18th to 21st March, 1918.

Load factor—69 per cent.
Annual load factor for 1918=53 per cent.

The ground is rather shallower than usual, the depth dredged being about 21 to 22 feet.

The power used on the dredge is generated by a hydro-electric plant and transmitted $4\frac{1}{2}$ miles to Bentong.

There is one 800 kw. alternator only, driven by an overhung Pelton wheel with two nozzles furnished with needle-valve hand regulation and deflecting shutter automatic regulation worked by an oil-pressure governor belted to the shaft. The exciter is belt driven also and an extra flywheel is provided in order to take care of heavy momentary fluctuations.

Current is generated at 2,200 volts and stepped up to 11,000 volts by three single-phase oil-immersed air-cooled transformers connected in delta.

The switch panel contains one oil switch with automatic release and the usual ammeters and voltmeters.

As the plant was intended to supply power for other mining purposes as well, it is a great deal too large to run a single dredge; in fact the maximum output so far has not exceeded 320 kw.

A unique feature of the installation is the use of water containing an abnormal amount of sand in suspension. The water is diverted from a mountain stream by a dam into an intake, and it then flows in a 36-inch pipe laid to a grade of about 1 in 70 to a settling basin.

At the bottom of this pipe, where it is supported in places on trestles are fixed three sand traps which consist of funnel-shaped castings with a 20 inch × 18 inch opening terminating in a 4-inch nozzle. These are kept full open at all times and discharge large quantities of coarse sand, the remainder of the sand being carried along to the settling basin.

This basin consists of a tank built of reinforced concrete and of the dimensions given in the plan shown in Fig. 10. The water entering is slowed down and deposits the coarser sand in the first compartment; the water still containing a certain amount of solid matter then flows over the skimming boards and into the pipe. The system is fairly effective and 3 or 4 feet of sand are scoured out of the first chamber every other day, but if the plant were running at its full power the tank capacity would have to be largely increased.

When measured, the water at the intake contained 280 grains per gallon and at the outflow from the settling basin 50 grains less, but the amount of solid varies from day to day and is said to be at times as much as 8,000 grains per gallon at the intake and 2,000 at the Pelton wheel.

The water from the tank outlet is piped to the Pelton wheel at which the head is 475 feet; this gives a theoretical discharge velocity of 174 feet per second.

There is naturally a considerable amount of wear of nozzles, needles and buckets. The plant has now been running 2 years, and it has been necessary to change the nozzles and needles fairly often and the buckets once; but the fact remains that the presence of considerable amounts of solid matter in water does not prevent its use with moderate spouting velocities. It must, however, be remembered that the flow in the pipes is at present only about 1·4 feet per second, whereas the pipes were designed for an ultimate flow of 5·45 feet per second. At this latter velocity there is a possibility of scour in the pipes themselves.

With a higher head and therefore greater spouting velocity it is possible that the use of such dirty water would have been impracticable.

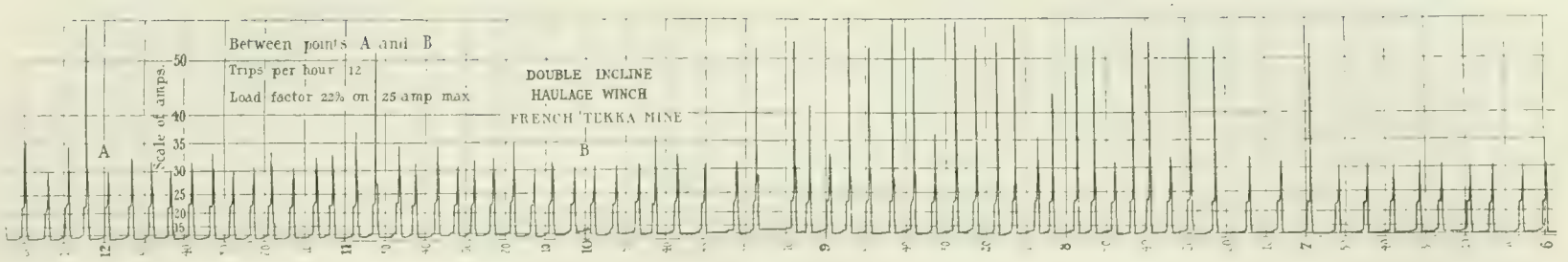


FIG. 8.

TABLE 5.

Particulars of Motors on Bentong Dredge.

Drive	B.H.P.	Volts	Rotor	Starter	Syn. Speed, r.p.m.	Rope and other Speeds. Remarks
Bucket chain and ladder winch ...	150	2,200	Wound	Rotor resist.	720	Bucket line speed 56 ft. per min. Winch drum speed 76 ft. per min. Triple purchase tackle to lift
Mooring winch	25	220	Wound	Rotor resist.	1,200	General service drum: H.S. 56 ft. per min., L.S. 18 ft. per min Other drums: H.S. 50 ft. per min., L.S. 16 ft. per min. Spud tackle triple purchase
Revolving screen	35	220	S.C.	Auto-trans.	1,200	
Low-pressure pump	150	2,200	S.C.	Auto trans.	720	Direct coupled. Supplies water to sluice boxes
High-pressure pump	200	2,200	S.C.	Auto-trans.	900	Direct coupled Supplies water to screen
3-in. service pump	10	220	S.C.	Auto-trans	1,800	Direct coupled. Supplies priming water to large pumps
Stacker belt	25	220	Wound	Rotor resist.	1,200	Belt and gear drive

For load curve see Fig. 7.

Sand pump, jig, and ballast pump motors were installed but not used.

The transmission line consists of three No. 6 wires arranged in a 3 ft. 9 in. triangle.

The lightning arresters in the power house and substation are of the aluminium-cell type surmounted as usual with spark gap and charging device. Each phase has one set of cells, the bottom elements being joined to a busbar connected to the top element of a fourth cell which provides the path to earth. Thus between each line and earth and between line and line there are two cells in series. This arrangement has worked well and there has been no trouble from lightning or from disturbances incident on charging.

The line enters the substation via a set of disconnecting switches mounted on a platform fixed on the terminal pole, and all high-tension wires are terminated on strain insulators or on two pin insulators.

In the substation are two sets of single-phase transformers, the larger set of three 150-k.v.a. 10,000/2,300 volts supplies the dredge line through an oil switch, the smaller set of three 50-k.v.a. of the same voltage ratio supplies a line to a pump. Originally 2,000-volt porcelain-body fuse-switches were used to disconnect this line, but after a short trial they were found to be unsafe due to the porcelain cracking and an oil switch will replace them.

The connection from the shore to the dredge is made by a three-core cable. The cores are insulated with vulcanized indiarubber laid together and wrapped overall with five laps of varnished cambric; the cable is then served with compounded jute and armoured with galvanized iron wire. The weight of the cable is taken by barrels floating in the dredge paddock.

An illustration of the dredge is exhibited and particulars of the motors used will be found in Table 5.

PART III.

Local Conditions.

As local conditions, more especially in regard to climate, labour and transport, are very different from those prevailing in temperate climates, the authors venture to put forward their views on certain points which are of considerable importance to owners of electrical installations in the Federated Malay States; they also wish to draw attention to certain details in the specification of machinery which, often disregarded entirely, are of vital importance.

Climate.—The climate of the Malay Peninsula is moist and hot, the shade temperature rarely exceeding 90° F.

There are no clearly defined seasons, but spells of wet and dry weather occur at certain periods of the year. During rainy seasons thunderstorms of tropical violence are experienced daily, generally in the afternoon or evening.

The rainfall varies in different districts from 90 to 130 inches for the year.

Standards Recommended.*

Generator pressures.—Alternating current: 440; 550; and 2,200 volts.

Direct current: 115; 240; 460; and 550 volts.

It is not advisable to generate at a higher pressure than 2,200 volts owing to the rapid deterioration of insulating materials due to the moisture-laden atmosphere.

Pressures at high-tension terminals of step-up transformers.—2,200; 3,300; 6,600; and 11,000 volts.

So far 11,000 volts is the highest pressure in use, but there is no particular reason why higher voltages should not be used if necessary, at any rate up to 20,000 volts. For higher voltages special precautions on account of the dampness of the atmosphere would probably be necessary.

Pressures on motor or consumers' terminals.—Alternating current: 100; 230; 400; and 500 volts.

Direct current: 110; 230; 440; and 500 volts.

Frequency: 50 periods.

For new installations the authors recommend a voltage of 400 at motor terminals for a three-phase alternating-current system. This is the most usual voltage and its adoption would facilitate linking up and encourage local agents to keep stocks.

Tests and temperature rises.—It is a common sight to see motors which have been rated on the assumption that they would be used in a temperate climate, working continuously up to their full load as marked on the name plate and even at overloads; this accounts to a great extent for the large amount of rewinding that has to be done.

The temperature of the air should be taken as 95° F. under cover, and the following temperature-rises should not be exceeded:—

(*a*) Generators and open and protected type motors after 6 hours' run at full load, 63 degrees F.

(*b*) Motors driving intermittent loads (winches for instance) after one hour's run at full load, 70 degrees F.

(*c*) Enclosed and pipe-ventilated motors are seldom used and tests prescribed should be drawn up to suit each special case.

(*d*) Oil-cooled transformers: maximum temperature of oil not to exceed 170° F. at continuous full load.

(*e*) All standards and tests other than the above to be in accordance with British Standards as recognized by the Institution, allowing for the higher temperature of the air.

It may be considered that the temperature-rises for generators and motors are on the low side, but in a country where facilities for re-winding are doubtful and where motors are often put to work for which they were never originally intended, it is as well to be on the safe side even if it costs a little more.

Specification of Machinery for the Federated Malay States.

Boilers.—The watertube type is most suitable. These have been so far always set in brickwork, but the use of the marine type with steel casing would probably be an advantage, as neither material nor labour for brickwork is good.

To keep the number of spares a minimum a type using one length of tube only is advisable.

* British Standards are recommended in all cases except as regards the voltage of 230; this voltage is in universal use in the Federated Malay States and Straits Settlements, and there seems no sufficient reason to abandon it.

Mechanical stokers.—The type of coal used as a rule, " Rawang smalls," is very suitable for firing on chain-grates.

Stack.—A short steel stack with induced draft is the best arrangement.

Coal-handling plant.—It is not possible to store Rawang coal for any length of time as it fires, so the arrangement made should aim at a steady continuous supply from truck to stoker hopper ; the experiment of storage under water will probably be tried in the near future, but it is doubtful if this class of coal is suitable.

Prime movers.—Turbines are being used for plants of 500 kw. and over. There are no special considerations except that larger condensers will be required than in England, as the temperature of the cooling water will be about 86° F. to 90° F. if water is returned from a cooling pond.

Alternators.—Subject to reduced temperature-rises British Standard practice gives every satisfaction.

Switchgear. For high pressures the most suitable is the totally enclosed ironclad sliding-carriage type. It must be insect and lizard proof, all ventilating holes should be covered with fine gauge wire netting, and all instruments should be enclosed.

For low and medium pressures the ordinary marble-panel central-station type is quite satisfactory. Here, again, precautions must be taken to prevent the entry of various small insects, especially into instruments.

Where step-up transformers are used the isolating switches, and oil switches if any, on the high-tension side may be placed in cubicles near the transformer in order to shorten the length of the bare wiring, the oil switches being worked by levers from the main switchboard.

Cables and connections in power house.—For high pressures multicore paper-insulated lead-sheathed armoured cable should be used, and must be properly sealed and divided at the terminals. The dividing boxes at the switchboard end should be incorporated in the switch panel.

For low and medium pressures rubber-insulated cables may be used.

Transformers.—If earth shields between primary and secondary windings are not provided, provision should be made for earthing the neutral of the low-tension winding.

In view of the difficulty of drying out transformer windings after they have been immersed in oil, it is recommended that moderate sizes should be shipped in oil from the factory.

Air-cooled transformers are not desirable.

Transmission lines.—The range of temperature experienced varies between 60° F. and 130° F., and as there is no ice or snow to contend with, a lower factor of safety can be used than that specified by the Board of Trade, but it is not usually necessary.

The height of lines must not be less than 22 feet, so that steel poles are advisable, wooden poles of the necessary length being expensive and hard to obtain.

Where cast-iron bases are used, the steel tube should pass through this to the bottom of the cast-iron base, and the cast iron should not be relied on to take the strain.

With steel poles an earth wire is essential.

Lightning protection.—At certain periods of the year thunderstorms are of frequent occurrence, and lightning is very severe in some localities.

Various types of arresters are used, but the authors are of opinion that protection for overhead lines can best be obtained by :

(1) The use of step-up and step-down transformers for all but very short lines and by heavily reinforcing the insulation of the transformer coils nearest to the line, in conjunction with arresters of the horn type with carbon resistance in series with the earthed horn, or with electrolytic arresters.

(2) An earth wire above the power wires earthed at frequent intervals.

(3) Earthing the neutral point of the generator and step-down transformer on the low-tension side.

It is a striking fact that in no case within the authors' knowledge where step-up and step-down oil-cooled transformers have been used has damage by lightning been experienced other than to the line ; on the other hand, in those plants where air-cooled transformers

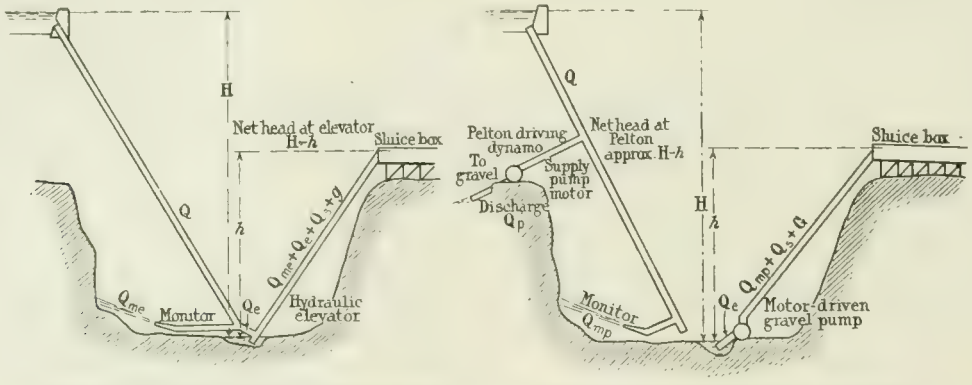


Diagram of divided-volume system using hydraulic elevator.

Diagram of divided-volume system using electrically-driven gravel pump.

FIG. 9.

have been used or the generators have been connected direct to the line, failures of transformers, switchboard instruments, and generators, have invariably occurred even where earth wires have been used.

Lighting circuits.—A voltage of 230 must not be exceeded, and this may best be obtained from a small transformer single or three phase; if single phase the centre point of the winding should be earthed, if three phase the neutral point. The voltage between any two wires should not exceed 230. There have been several fatalities due to shock on alternating-current lighting circuits where the potential to earth was 230 or over.

Mine distribution.—This is invariably by overhead wires on hard wood pole lines, the minimum height being nominally 18 feet.

The motors are usually placed in temporary sheds, and connections between lines and switchgear are made by rubber cables, bare wires not being allowed within 7 feet of any building. Rubber insulation lasts about 18 months if exposed to the weather, but so far no satisfactory substitute has been found to replace it; probably three-core rubber-insulated armoured cable would last longer, as the rubber would be shielded from the direct rays of the sun.

Where high-pressure leads enter a temporary building a three-core paper-insulated lead-sheathed armoured cable with proper terminal boxes and bonding appliances is called for.

Mine switchgear.—The only type that can be called safe is the totally enclosed interlocked ironclad type. It is now so moderate in price that there is no excuse for the employment of any other.

In the past, makers have supplied totally unsuitable switchgear, chiefly bare knife switches and bare fuses mounted on heavy marble panels. This apparatus was often to be found unfenced over a wet floor and under the charge of a bare-footed coolie.

No-voltage and overload releases should be fitted in all cases.

All iron work and motor frames must be earthed, and usually this means an earth plate to every motor.

Mine motors.—Motors wound for voltages above 500 are not necessary for the majority of mining work and, except in large sizes, are undesirable.

Former-wound stator coils should be used in preference to hand winding. With semi-closed slots it has been found that coils of the "cut and push through" type are the most satisfactory. The slot insulation of all former-wound coils should be of mica moulded on to the coil after winding, the coil being treated under vacuum with suitable impregnating solution before being placed in position in the slot.

Trouble with hand-wound coils has been frequently experienced, more especially in high-voltage motors, due to the difficulty of packing the wires tightly inside the slot and excluding air.

Manufacturers also frequently wind the coils so that the end turns are adjacent and have to withstand the full voltage of the coil.

Where speed regulation is specified, brushes and slip-rings should be of liberal design, and the latter should be well spaced to prevent short-circuits in starting. The most satisfactory type of resistance is the cast-iron grid, trouble having been experienced with liquid resistances.

The connections between switch-panel and starter and between rotor and resistances are best made by three-core armoured cable equipped with sealing boxes, but single-core rubber-insulated cable if properly protected is quite satisfactory for medium pressures.

Winches.—The usual duty required of a winch is to haul loads of three or more trucks containing about $\frac{3}{4}$ yard of karang up an incline, which varies in length and grade, at the rate of about 12 trips an hour, the ascending trucks being partly balanced by the descending empties.

The conditions vary in different mines and must be specified in each case.

The winch should be of the double-drum variety with motor, resistances, switches and tramway-type controller mounted on a bedplate of structural steel, the whole arrangement being as portable as is consistent with strength.

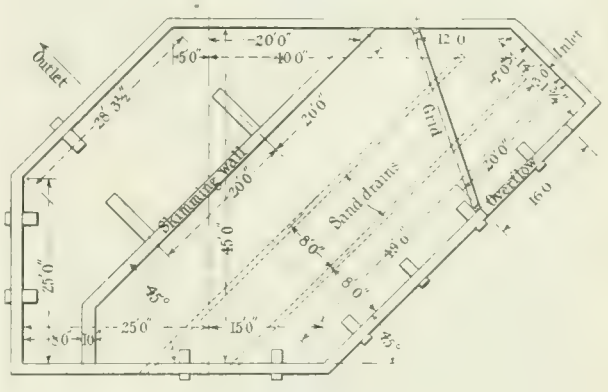


FIG. 10.—Plan of settling basin, Tin Bentong Mine.
Total depth = 11 ft.

The best arrangement is to mount driving spur wheel and band brake between the drums; this, without unduly increasing the width of the winch, gives the drums a wider pitch. The pitch of the rails is usually from 4 ft. 6 in. to 6 ft. 6 in., and a drum pitch of 3 ft. 9 in. gives good results. If the pitch is too narrow the turns on the drum ride over one another and cause undue wear of the ropes, besides danger of sudden jerks to the rope. One of the drums should be capable of rotation about the shaft when necessary for adjustment of the ropes, and this is usually effected by means of a clutch. One band brake held off by the driver's foot is sufficient in most cases.

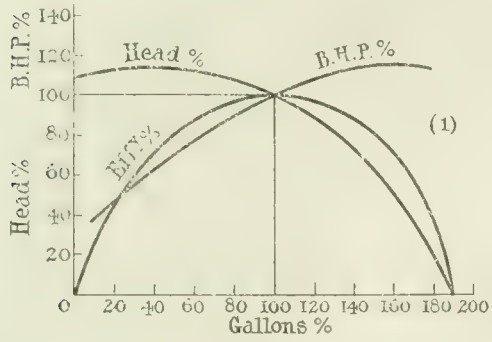
Electric braking has not been a great success and is generally unnecessary.

A recording-ammeter chart of a typical winch will be found in Fig. 8.

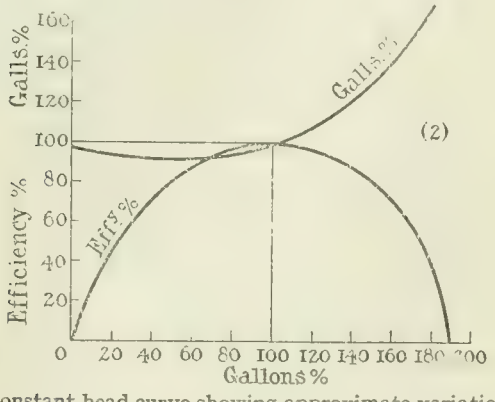
Puddler drives.—A puddler drive presents a fluctuating load. In the case of a single high-speed puddler the normal power absorbed is about 12 b.h.p., which rises to 24 whenever a lead of karang is dumped and continues at that point for about one minute. As a high-speed puddler runs at 120 r.p.m. it is usual to employ a single-reduction back-geared motor in conjunction with a belt drive, a flywheel being generally used to help the

motor at the moment the karang is dumped. Gears should run in an oil bath, otherwise owing to the dust and grit which is always about they become intolerably noisy.

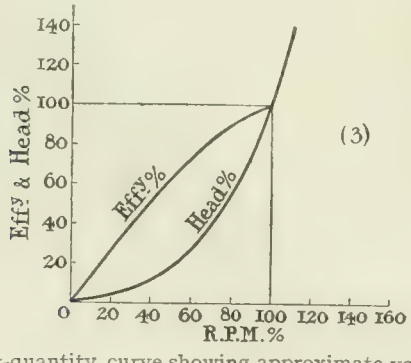
Low-speed puddlers run at about 5 to 9 r.p.m. and



Constant-speed curve showing approximate variation in quantity for a variable head in per cent of the normal.



Constant-head curve showing approximate variation in quantity for a variable speed in per cent of the normal.



Constant-quantity curve showing approximate variation in head for a variable speed in per cent of the normal.

FIG. 11.

the power absorbed is about 8 to 13 b.h.p. per puddler. They are generally run in groups of two, and being larger and having a great inertia the fluctuations of current are not so great.

Pumps.—A whole treatise might be written on the subject of the use and abuse of pumps in mining. The centrifugal pump is invariably used, and wisely so, as the water pumped contains certain quantities of grit in all cases.

Unfortunately, it is almost impossible to place a pump and continue to work it for any length of time where it can show its best performance; sooner or later it will be put to work at an unsuitable head. The number of units wasted by the use of centrifugal pumps under unsuitable conditions must be enormous.

Purchasers of pumps should obtain characteristic curves for each pump they purchase: these will be supplied gladly by first-class makers. These curves should be of the nature of the set in Fig. 11, and with this information the effect of variations of speed, head and quantity can be forecasted and the pump run under the most favourable conditions. Without this information, however, one can only guess.

Where speed variation is necessary with three-phase motors this, if moderate, may be obtained by the use of rotor resistances; but if a larger variation is required a belt drive is generally adopted.

Specification of Electrically-driven Bucket Dredges.

Cables.—The cables for connecting the dredge to the shore calls for special features; it must be flexible, mechanically strong, impregnable to moisture and continual change of conditions, since it is alternately immersed in water and exposed to the sun. It should also be as light as possible.

The type of cable used on the Tin Bentong dredge has been found satisfactory over a period of two years. A specification of this cable is given under the description of the Tin Bentong dredge. The armouring of this cable, however, shows signs of corrosion, and the authors therefore recommend that armouring should be heavily galvanized and covered with a protective compounded braiding.

The cables for connecting the motors to the low-tension switchboard should comply with the following specification:—

The cables to be three-core, each core with one wrapping of paper covered with four tapes of varnished cambric, the cores being laid together and served with compounded jute, covered with a layer of varnished cambric and braided overall. The motor cables should be run in piping clamped to the framing of the dredge.

Motors.—All motors should be designed for a working voltage of 400.

The bucket-line motor has the most exacting duty of any to perform, since it is liable to sudden shocks and overloads caused by the buckets coming into contact with limestone pinnacles, clay banks, or submerged timber. It must be reversible and capable of running slowly at light loads to permit of inspection and repairs to buckets. The speed regulator can be of the grid or liquid type; the former will probably be found more suitable in practice, as clean water is not always obtainable from the dredge pond.

The remaining motors of the dredge equipment call for no special features; they must all be of the protected type, drip-proof and capable of carrying their rated

full load with a rise in temperature not exceeding 63 degrees F. with continuous operation.

The horse-power of the motors required varies considerably according to the nature of ground treated, size of buckets, and digging depth.

The aggregate capacity of motors installed for a dredge capable of treating 75,000 cubic yards of solid per month at a depth of 50 feet would be approximately 300 b.h.p. The digging capacity of dredges now installed in the Federated Malay States varies from 70,000 to 120,000 cubic yards per month.

The following table gives the rating of the bucket-line motor on some American dredges.

Place	Size of Bucket in Cubic Feet	Buckets per Minute	Motor, h.p.	Average h.p. Input
Oroville ..	5	18	75	65
Marysville ..	7	20	150	140
Conrey ..	9	18	150	185
Natoma ..	14	21	400	285
Conrey ..	17	22½	550	460

The total consumption of power per cubic yard treated for a moderate-sized dredge would be approximately 1·7 kilowatt-hours.

The authors are of opinion that for a group of electrically-driven dredges there would be a saving of £100 per dredge per month over a steam-driven dredge.

Conversion from Steam to Electric Drive.

The advisability of converting existing steam dredges to electrical drive is a question which may present itself to the mining engineer in the near future, and before reaching a decision the following points must be considered :—

(1) Lifetime of property, efficiency of existing steam plant, and whether the existing plant will efficiently last the life of the dredge.

(2) Location of dredge and facility of fuel transport.

(3) Cost of fuel.

(4) Cost of conversion to electric drive, and time required to make the conversion.

Lode Mining.

Lode and alluvial mining present entirely different problems and when, as at present, tin of greater purity can be won more easily in alluvial workings there is not much likelihood of great efforts being made to develop lode mines where the rock has to be blasted out and crushed under stamps in order to bring it approximately to the state in which it is found in alluvial workings.

The Government of the Federated Malay States recognize the greater difficulty of lode working, by granting a rebate in certain cases on tin ore produced by this means.

In the future, however, when the alluvial deposits have been turned over and over by processes of increasing efficiency until their valuable contents have been exhausted, a time will come when lode mining will receive more attention.

There are only about half a dozen mines of any importance coming under this category in the Federated Malay States, two of them very small, but another, Pahang Consolidated, the largest producer in the F.M.S. and probably the second largest in the world.

In nearly all these mines electricity is in use to some extent and its use is being extended, and as lode mining on anything but a very small scale is sure to be carried out by European companies in future, we may look forward to the time when there will be a fairly heavy demand for electrical power from this source.

The engineering problems in lode mining need not be discussed at length as they are practically similar to those encountered in gold mining.

Power is required underground for pumping and hauling and drilling, and on the surface for driving rock crushers, stamps, tables and other tin dressing machinery.

A few particulars of two lode mines will be found in Table 3.

Conclusion.

The authors in conclusion, wish to thank the managers and engineers of all the mines mentioned in the body of the paper or in the Tables, for supplying the data without which the writing of this paper would have been impossible. In some cases special records have been kept for the purpose, and in others much time has been spent in looking up and classifying old data, and the authors very much appreciate what has been done : they also have to thank Mr. W. Eyre Kenny, M.Inst.C.E., Senior Warden of Mines, F.M.S., and the Bucyrus Company for much useful information.

Finally the authors would urge all mine managers to install proper recording instruments and to keep accurate records of power costs as a matter of routine ; by omitting to do so one of the advantages of the electric drive is thrown away.

APPENDIX.

Hydraulic-Electric Mining.

List of Symbols.

Q = Total pressure water available, cubic feet per min.

Q_M = Monitor water in cubic feet per min. under net head H_N feet.

Q_S = Seepage and other water in addition to monitor water that has to be raised from the mine.

Q_P = Pelton wheel water in cubic feet per min. under net head H_P feet.

Q_e = Elevator water (c.f.m.) under net head H_e feet.

H = Total net head, available feet.

h = Lift in feet from sump to sluice box.

H_N = Head developed by nozzle pump.

G = Gravel raised in cubic feet per min.

Efficiencies.

Hydraulic elevator	16·6 per cent.
Gravel pump	38 per cent.

Low-tension Hydro-electric Plant.

Pelton wheel	0·70	Overall 0·23, i.e. 23 per cent.
Generator..	0·93	
Distribution	0·98	
Motor ..	0·88	Motor and pump only 33·4 per cent.
Pump ..	0·38	

High-tension Hydro-electric Plant.

Pelton wheel	0·76	Overall 0·195, i.e. 19·5 per cent.
Generator..	0·93	
Step up ..	0·975	
Line ..	0·90	
Step down	0·97	
Distribution	0·98	
Motor ..	0·88	Motor and pump only 33·4 per cent.
Pump ..	0·38	

Where electrical conditions differ, a suitable efficiency figure must be calculated and substituted in the following equations.

SYSTEM 1.

Ground *sluicing* with gravel pumps or hydraulic elevators.

Work to be done in elevating mixture.

$$(Q_S \times 62{\cdot}3 + 100\ G)\ h \text{ ft. lb. per min.}$$

Work obtained from gravel pumps, ft. lb. per min.

$$(Q_P\ H_P \times 62{\cdot}3 \times 0{\cdot}23 = Q_P\ H_P \times 14{\cdot}3) \quad . \quad . \quad (1)$$

Work obtained from elevators, ft. lb. per min.

$$(Q_E\ H_E \times 62{\cdot}3 \times 0{\cdot}166 = Q_E\ H_E \times 10{\cdot}3) \quad . \quad . \quad (2)$$

But $H_P = H_E = H - h$

$$\therefore\ Q_P : Q_E :: 103 : 143$$

There is a saving of 28 per cent in water by using gravel pumps for the same work done in elevating.

SYSTEM 2.

(*See Figs. 5 and 9.*)

Hydraulicing under natural head, with gravel pumps or elevators. Full available head used at monitors.

Useful work to be done by pumps or elevators, ft. lb. per min.

$$\left\{(Q_M + Q_S)\ 62{\cdot}3 + 100\ G\right\} h \quad . \quad . \quad . \quad . \quad (3)$$

If Q_S is 10 per cent of Q_M and G 7 per cent of Q_M we get

$$75{\cdot}53\ h\ Q_M \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

Using pumps,

$$Q_P\ H_P \times 14{\cdot}3 = 75{\cdot}53\ h\ Q_{MP} \quad . \quad . \quad . \quad . \quad (5)$$

Using elevators.

$$Q_E\ H_E \times 10{\cdot}3 = 75{\cdot}53\ h\ Q_{ME} \quad . \quad . \quad . \quad (6)$$

[NOTE.—Q_{MP} and Q_{ME} = monitor water (cubic feet per min.) using pumps and elevators respectively.]

$$\frac{Q_{ME}}{Q_E} = \frac{10{\cdot}3\ (H - h)}{75{\cdot}53\ h} \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

(NOTE.—If G = 5 per cent of Q_M equation (4) becomes $73{\cdot}53\ h\ Q_M$.

$$\frac{Q_{MP}}{Q_P} = \frac{14{\cdot}3\ (H - h)}{75{\cdot}53\ h} \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

From (7) and (8) we get

$$\frac{Q_{ME}}{Q} = \frac{0{\cdot}136\ C}{0{\cdot}136\ C + 1} \quad . \quad . \quad . \quad . \quad (9)$$

$$\frac{Q_{MP}}{Q} = \frac{0{\cdot}189\ C}{0{\cdot}189\ C + 1} \quad . \quad . \quad . \quad . \quad . \quad (10)$$

where $C = \frac{H - h}{h}$.

These equations give the proportions to total of monitor water available when using gravel pumps and elevators respectively, and Fig. 5 has been prepared by their use.

SYSTEM 3.

Hydraulicing under natural head, with gravel pumps.

Divided-head System. High-tension Transmission.

In this case equation (5) becomes

$$Q_P\ H_P \times 12{\cdot}1 = 75{\cdot}53\ h\ Q_M \quad . \quad . \quad . \quad (11)$$

as $Q_P = Q_M$ since all water passing Pelton goes to monitors

$$\frac{H_P}{h} = 6{\cdot}2 \quad . \quad . \quad . \quad . \quad . \quad . \quad (12)$$

In words, the fall to the power house must be 6·2 times the height of lift.

From equation (12) the curves in Fig. 6 have been prepared.

SYSTEM 4.

Hydraulicing under head wholly or partly produced by pump, lifting by gravel pump.

The pump efficiency will be about 60 per cent, giving an overall efficiency from turbine nozzle of 36·5 per cent.

Total power available at power house

$$= Q\ H \times 62{\cdot}3 \text{ ft. lb. per min.}$$

Work done in raising gravel and water is as before

$$\left\{(Q_M + Q_S)\ 62{\cdot}3 + 100\ G\right\} h$$

But power has, in addition, to be furnished to put Q_M under a head H_N.

Total power required at power house, ft. lb. per min.

$$= \frac{\{(Q_M+Q_S)\,62{\cdot}3+100\,G\}h}{0{\cdot}23} + \frac{Q_M H_N \times 62{\cdot}3}{0{\cdot}365} \quad . \quad (13)$$

or if 10 per cent seepage and a 7 per cent mixture are assumed as before, this equation becomes

$$\frac{75{\cdot}53\,h\,Q_M}{0{\cdot}23} + \frac{Q_M\,H_N \times 62{\cdot}3}{0{\cdot}365} \quad . \quad . \quad . \quad (14)$$

$$\therefore\ Q\,H \times 62{\cdot}3 = Q_M\,(328\,h + 170\,H_N) \quad . \quad . \quad (15)$$

By varying the efficiency figures in (13) to suit the case, the power required for a steam or other plant may be calculated.

Gravel Pump Tests.

Test 1.—Average of several runs at different times.
Gravel pump, 8 in. delivery.
Motor, 120 b.h.p.
Q = Water pumped = 298·5 c.f.m.*
G = Solids = 18·22 c.f.m.
U = Units used per hour = 52·6.
h = Lift = 43 ft.

Efficiency of pump and motor

$$\frac{h\,(Q \times 62{\cdot}3 + G \times 100)}{U \times 44{,}240} \quad . \quad . \quad . \quad . \quad (16)$$

[Note.—1 unit per hour = 44,240 ft. lb. per min. Substituting, this works out at 37·8 per cent.]

Allowing a motor efficiency of 85 per cent,
Efficiency of pump = 44·5 per cent.

Test 2.—Gravel pump, 6 in. delivery.
Motor 40 b.h.p. 5 days' run.
Q = Water pumped = 131·4 c.f.m.
G = Solids = 7·155 c.f.m.
U = Units used per hour = 25·48.
h = Lift = 42 ft.

Efficiency of pump and motor using the same formula = 33·17 per cent.
Allowing a motor efficiency of 85 per cent,
Efficiency of pump = 39 per cent.

Test 3.—Average over a year.
Pelton-wheel drive direct-coupled to 8-in. gravel pump.

* "C.f.m" is used in these calculations for "cubic feet per minute."

Water raised = 261·8 c.f.m.
Gravel raised = 18,000 cubic yards per month.
Lift = 45·7 ft.
Water used by Pelton wheel = 88·44 c.f.m.
At net head = 500 ft.
Then useful work done by Pelton wheel allowing 75 per cent efficiency = $88{\cdot}44 \times 62{\cdot}3 \times 500 \times 0{\cdot}75$.

18,000 cubic yards per month average is 11·09 c.f.m.

Theoretical work done in raising water and gravel

$$= 45{\cdot}7\,(261{\cdot}8 \times 62{\cdot}3 + 11{\cdot}09 \times 100) = 17{,}419{\cdot}14 \times 45{\cdot}7.$$

$$\text{Pump efficiency} = \frac{17{,}419{\cdot}14 \times 45{\cdot}7 \times 100}{22{\cdot}44 \times 62{\cdot}3 \times 500 \times 0{\cdot}756} = 38{\cdot}5 \text{ per cent}$$

Hydraulic Elevators.

Test 1.—Average over a year. From Mr. J. J. Garrards' paper published in Bulletin No. 149 of the Institution of Mining and Metallurgy.

H = 127 ft.
Q_E = 330·4.
Q_M = 212·3.
Q_S = 15.
G = 10·98.
h = 23·3.

$$\text{Elevator efficiency} = \frac{h\{(Q_M+Q_S)\,62{\cdot}3+100\,G\}}{62{\cdot}3\,Q_E\,(H-h)} \quad . \quad (17)$$

Substituting figures as above,

Elevator efficiency = 16·58 per cent.

Test 2.—*Hydraulic elevators during* 1917 *on Gopeng Consolidated.*—Average over a year.

H = 403·7 ft.
Q_E = 311·4
Q_M = 204.
Q_S = 0.
G = 12·6.
h = 70.

Using formula (17), elevator efficiency = 15·1 per cent.

[Note.—All gravel pump and elevator efficiency figures in this paper include frictional pipe losses under average mining conditions where the run of piping is kept as short and free from bends as possible.]

Discussion before The Institution, 18 December, 1919.

Mr. W. H. Patchell: The authors seem to have fallen on rather evil times, for I notice that in 1913 they had 50,000 tons' export, whereas it was stated in the *Times* of yesterday that the export of tin from the Federated Malay States was steadily decreasing: it had gone down to 47,000 tons in 1915, 37,000 tons in 1918, and for the first 9 months of this year only 28,000 tons had been exported. Of course it will be highly important with that decreasing output to take every possible step to reduce the cost. To take what may seem to the authors a technical objection, to one who is used to working in English mines the places dealt with in the paper are not mines at all but quarries. A mine in England is a covered mine. Open work is a quarry and not a mine at all. Of course the same rules and regulations apply. On page 173, where mention is made of open cast mining, hydraulic mining and bucket dredging, I take it that there an open cast mine is practically an open quarry worked by hand or by hydraulicing. I also take it that in No. 2 it is an open cast

mine worked by hydraulicing only, and that No. 3 is practically a pond which is worked by bucket dredging. Those who have seen a bucket dredger at work must have been impressed by its enormous size and its unwieldiness. The authors are not mining engineers—they are only looking at the subject from the electrical point of view—but when one sees the shrinkage of the output of tin from the Federated Malay States one wonders what the efficiency of recovery is. The puddling described on page 173 makes slimes, and unless there are some very careful steps taken those slimes are to a great extent lost and it is left for somebody else to work the ground over again when more efficient methods of recovery are adopted. The description given on page 173 is just the way to make slimes. Small pieces of tin may be ground round with the gravel into excellent slimes. I am sorry to have to refer again to something of which I have complained elsewhere. Why should we call what is essentially an English invention a semi-Diesel? * It is not a semi-Diesel engine at all. It is a hot-bulb engine which the authors mean, I think, and it is a pity to go abroad to find a name for what is essentially an English invention. It was first worked out by Hornsby's under the Ackroyd Patents and now many firms make it. On the first page the authors speak of 7,600 kw. of generating plant and 8,300 h.p. of motors, but they do not tell us how many "mines" there are. They suggest that coupling up and interconnecting is a good thing, but then we are told that there are very heavy rentals for wayleaves. Are we going to get in the Federated Malay States the trouble which we have had in this country with wayleaves, or are some special remedies to be introduced? I agree with the authors' statement on page 175 that steam users with a certain maximum horse-power installed have a way of over-estimating the h.p.-hours. We find it over and over again when we are considering driving propositions. In the same way at the end of the paper the authors suggest that all mine managers should install proper recording instruments, for they are often as big sinners as the steam users. They do not know what their motors take to work, and neglecting the facility for the ready checking of electrical driving they cannot fully appreciate its advantages, and they use it in almost as clumsy a way as steam driving. It is a little difficult to follow the authors in their different classes of mining. I take it hydraulic mining is the washing down by a monitor and ejecting the washed-down material with an hydraulic elevator, and that the hydraulic-electric is washing down by a monitor and lifting the washed-out material with a gravel pump. The authors show one pattern of gravel pump, the Thompson. This is a type of centrifugal pump with a very crude internal cast-iron lining, so that the inside parts can be readily renewed as they become worn. Then we come to the suction dredge. A little further on in the paper the authors mention the gravel pump on the suction dredge, but they skip the nozzle pump and do not tell us what power it takes. If one wishes to compare the power taken by a bucket dredge with a suction dredge, one has not got the figures in the paper. It would be useful if the authors would give them. In the suction dredge, a suction pipe is not going to pick up hard consolidated gravel. We have to loosen such gravel with an hydraulic jet so that the suction dredge has to be fed practically with a high-pressure under-water monitor. That, I take it, is what the authors are describing here when they allude to churning up the gravel. When we have a bucket dredge we put the spuds out behind the dredge to prevent it going backwards, and force it forwards by driving the buckets into the material. The suction dredge will not do that. It will pick up loose stuff but not consolidated stuff unless this is first broken. The authors give us the horse-power of the main pump but not of the hydraulic "poker" which is used to stir up the stuff. As the authors remind us, we are up against the old trouble of alternating current versus direct current. If we had not had so much trouble with commutators in the old days, I do not think we should have as much trouble now with slip-rings. People turn their backs on direct current and adopt slip-rings, to find sometimes that they are going out of the frying pan into the fire. I know one country now where they are trying to make a rule that no direct current shall be used at all, but that everything shall be alternating current. It will be a great pity if such a rule is made, because, whatever devices are introduced, alternating current is not as convenient as direct current for speed regulation. The best method of regulating alternating current is more or less inefficient, and so much work is best done with variable-speed motors. If it is a really serious job, what happens is that a motor-generator is put in and the work done by direct current. The authors mention the pressure used for hydraulicing. They say there is no economy in using pressures higher than about 200 lb.—call it roughly 400 ft. I quite agree there is not, but they mention in one place 50 ft. That is only about 25 lb., and that is not high enough to do any real good. When we are hydraulicing we have to make the force of our jet such as will loosen the material, but we have to get as much water running through that jet as will wash the material away and therefore we have to get a certain relation, in view of the material which we are trying to loosen, between the pressure and the quantity. I should like to ask the authors why they quote lengths in "chains." Nobody except surveyors uses the term "chains" nowadays. There is an interesting point regarding the motors on the Bentong dredge. The dredge proper has a 150-h.p. motor to work the bucket chain, and a 25-h.p. motor for the mooring winch; call it 175 h.p. for the dredge proper. Thus there are 5 motors—total 420 h.p. for the auxiliaries, compared with 175 h.p. for the dredge only. How much work beyond the actual washing of the gravel is done on the dredge? If it has taken 175 h.p. to get the stuff out of the ground on to the dredge, and 420 h.p. for the motors to rough wash it, how much of the milling of the tin is done on the dredge and how much is done elsewhere? Such figures are wanted when comparing the 175 h.p. for a bucket dredge with the data for a suction dredge. There is an interesting point with regard to the screening of the material after it has been got on board the dredge. It takes a 200-h.p.

* Since corrected.

motor to keep the screen clean. The high-pressure pump in the middle of the group, Table 5, supplies water to the screen, so it takes more power and water to keep the screen clean, and that is not the water which is going over the screen; it is only a sort of hydraulic poker to keep the stuff alive on the screen. The water which goes over the screen and which does the actual washing is supplied by the low-pressure pump. The description of the Federated Malay States' climate almost applies to England! Will the authors tell us what are the hygrometric conditions, because the care of motors and the care of cooling towers do not depend entirely on temperature; they depend a great deal on the hygrometric conditions? (If we go to the right place we can get 90 inches of rain a year in England.) Will the authors also tell us the elevation above sea-level? The authors recommend the British Engineering Standards Association's voltages, with the addition of 230 volts, which comes about by somebody running a middle wire from a 400-volt 3-phase star system. But then, after adopting the whole of the British Standards, with the addition of that one, they disagree with the temperatures. I absolutely agree with them. I think the tendency of the British Engineering Standards Association now is to take the temperatures too high, and I wish the authors could get them reduced. The switchboard conditions are rather amusing. They have to be insect-proof. We know that in this country we had to make them cat-proof and then rat-proof and mouse-proof. In the early days before meters were made so well as they are now, we had to make them cockroach-proof. On the top of page 187, the second column, what the authors call a winch is what we generally call a haulage. What is the common haulage speed adopted in the Federated Malay States? It is an interesting point. I have generally found that 6 miles an hour for haulages in which the trucks have to be handled frequently is quite fast enough, but for long haulages where handling does not matter much the speed can be raised rather higher. On the same point, the authors recommend a double drum for hauling on an incline. I have found a continuously running shaft with up to 4 drums on it very handy indeed. There is an important point which has not been taken into consideration in regard to these pumps. For mining work and rough work it is necessary to choose the pump so that if the head varies the motor will not be overloaded. That rather depends on the class of pump one is using.

Mr. Llewellyn Foster: The detail information which the authors have given can, I think, to some extent be compared with China clay working in Cornwall. Mr. Patchell has pointed out that these Straits mines are not really mines but quarries, and China clay is worked in a very similar sort of way. In China clay working we are up against the same kind of difficulty, first of all as to the amount of pressure to be used at the nozzle. That I may say does not, as a rule, exceed 100 to 120 lb. per square inch. One of the greatest difficulties with regard to the China clay gravel pumps is that they come across a lot of limestone. I was speaking to a well-known China clay manager to-day, and he tells me that originally they used a mesh on the suction of 1¼ inches, as he had been informed by the makers of the pump that the pump would be quite capable of dealing with anything which would pass through 1¼ inches. He soon found, however, that this was not the case because, if he got two 1-inch pieces going through, they promptly jammed inside and played havoc with the pump. Therefore he has now reduced the mesh until it has got down to ½ inch, and with such a mesh he finds quite satisfactory results. In a good many of the China clay quarries in Cornwall they work electrically, that is to say, they drive their pumps electrically, and the efficiency is quite satisfactory. I am sorry I cannot give any definite figures, as I have not had time to get them. They have a great deal of trouble, as might be expected, with the bearings of the gravel pumps. I do not know how long some of them last, but for a bearing to last six weeks is quite good. That difficulty has quite recently been overcome at one of the big China clay quarries by the adoption of a special bearing, and I was informed by the same manager that he has some gravel-pump bearings which originally would have worn out in six weeks but have now lasted for two years. So, whatever he has done, it is something very efficient. With regard to tin mining in Cornwall, no doubt many of the members know that practically the whole of the tin won in the United Kingdom comes from Cornwall, and none of the mining in Cornwall is carried out by the process described. The Cornish tin mines are real mines in practically every case, some being 300 to 600 fathoms deep. The ore is blasted out, taken to the top, and crushed. Thereafter the treatment is very much the same as that indicated in the paper. There are one or two questions which I should like to ask the authors. I have been looking at the Tables and trying to find out the units consumed per cubic yard treated Taking Table 1, "open cast mines," and working out the two first instances given, it comes to 5·3 units per cubic yard. If we take Table 2, "hydraulic-electric mines," and again take the first two cases, it works out to 4·6 units per cubic yard. If we take the "miscellaneous mines" in Table 3, again taking the first two cases, that works out to 1·9 units, which seems rather a curious drop. If we take the "French mine" in Table 4, that works out to 3 units per cubic yard. There seems to be a considerable variation, and I wonder if the authors can account for this. With regard to alternating current versus direct current, there is no doubt that where we are using gravel pumps, and in much of the machinery for driving tin-mining recovery, we must have a fairly close variation of speed; that is to say, we must be able to regulate within quite small limits. It seems to me that there is no possible way of doing that satisfactorily unless we use direct current, and, as Mr. Patchell suggests, if we can group mines together, why not put down a motor-generator and have direct-current motors? I was rather interested in the load curve of the power house on page 183, and have been trying to discover whether they worked in any particular kind of shift or whether there was any fixed time when the mine or dredge, as the case might be, was shut down. I am afraid I cannot

do this. With regard to the local atmospheric conditions, these are rather trying, but I doubt if they are any more trying than those in Australia. Those members who have been there know that there is not so much moisture as is mentioned in the paper, but it is usually very much hotter. Many years ago I was instrumental in putting some electrical plant into the Broken Hill silver mines. We had great trouble with the generators due to the fact that they were designed for working in England, but the initial temperature out there made them very unsatisfactory, and we used to have very frequent trouble. I see that the authors recommend a temperature rise of 63 degrees F. with the temperature of the air at 95° F. That gives 158° F., which seems very high. With regard to keeping the apparatus insect and animal proof, we found in Australia that a snake apparently could get through anything except cast iron. We found that no kind of box would keep snakes or insects out, at least not for any length of time. How they got through I do not know, but they did in the most extraordinary way, and when they do get through they accumulate together, and that is what finally causes the trouble. With regard to transformers, I should like to know if the authors can tell us whether they have had trouble with oil-filled transformers and, if they had, whether they took any steps, and, if so, what steps, to ascertain periodically the condition of the oil. We are having a good many breakdowns now in the United Kingdom with such transformers, and it is very often due to the oil. We have found that some users of transformers carry out really systematic examinations and tests of the oil. What they do is to draw oil off occasionally and examine and test it carefully. But if they do not do this systematically, and a transformer that has been working steadily for three or four years is lifted out of its case, everything will be found to be full up with sludgy oil and dirt. In some transformers, even of the best make, there are far too many traps or corners where the sludge will settle and from which it cannot be moved except by taking the whole of the winding out and cleaning it, and that is not easy to do. I should like to ask the authors whether they have tried transformers in which there is no air space at all, that is to say, which are entirely oil-filled, using a tank which gives a slight head of oil and keeps the transformer absolutely full of oil, with no air inside at all. That is a practice which seems to be coming into favour, more particularly with high-voltage transformers. I notice on page 187 the authors state: "There have been several fatalities due to shock on alternating-current lighting circuits where the potential to earth was 230 volts or over." Do they mean that those fatalities were really due to accident or due to somebody just touching a fitting or something of that kind? I note also what they say with regard to mining switchgear. I agree that the only safe type is the totally enclosed ironclad gear, but although we cannot expect to get a thoroughly good ironclad switchgear without paying for it, I do not think it is quite right to say that it is moderate in price. With regard to stator-wound coils, I see the authors recommend that after a coil has been wound it should be treated under vacuum with suitable impregnating solution before being placed in position in the slot. They say also there have been a great many re-windings. Have they found any difficulty in moving such coils after the motor has been in use for some little time? Our experience usually is that after the motor has been running, especially on nearly full load, for a fair amount of time, it is extremely difficult to carry out a stator repair without carrying out a rewind. Finally, I should be interested to know what is the cost of transport of the tin from the mines to where it is shipped. I imagine that most of it is shipped for long distances.

Lieutenant H. E. Crowcroft: I have had some little experience, both at home and abroad, in the operation of electrically driven plant on alluvial propositions—chiefly bucket dredges—and in this connection should like to support the authors emphatically on one point, namely, the supply of suitable equipment. We all know the extreme inconvenience and bad odour caused by unsuitable apparatus in electrically operated machinery, and this is obviously a policy which should be carefully avoided at all costs. As regards dredge equipment, to which my remarks chiefly apply, we in this country have not much opportunity of seeing the actual conditions on site. There were one or two fairly large dredges built some years ago in that once productive county of Cornwall, but I am afraid these plants dredged too deeply into the pockets of the shareholders. That was in pre-war days, so perhaps my information is now out of date, especially as the market price of the metal has risen considerably since then. But it would be a splendid object lesson to electrical designers to stand on the deck of a steel-built bucket dredge whilst it is cutting its way through dry land, especially if that land contains submerged forest, which is often the case. One then gets quite a good idea of what constitutes real shocks, jars, vibrations and heaving deck with copious quantities of water, mud and gravel deluging the place. Under these conditions it will be realized that everything of the very best design and material should find a place on board, weather-proof, fool-proof and shock-proof. Further, the load curve in Fig. 7 gives one an idea of the extreme and sudden variations in the power demand. The peaks, though frequent, are usually of short duration, and hence I would advocate efficient time-lags on the motor control-gear and, of course, first-class governors on the prime movers. As regards the wiring on board, I should have thought that the authors would rather have advocated three-core armoured cable with proper cable boxes at each end as being a more mechanical job than piping. This is, I believe, in accordance also with the best American practice. Although I understand that at present America perhaps leads the way in the matter of supply of electrical mining equipment for alluvial propositions, there is no reason why we in Great Britain should not have a fair share in this profitable business, especially in view of the fact that British capital is so largely and frequently invested in these and similar undertakings. It only requires that we should take a live interest in the actual working conditions to be met, instead of relying too much on works standard designs.

Mr. H. W. Couzens: I want to ask one or two questions. The chief thing is in regard to Table 1, in

which figures are given for power stations using different kinds of fuel. The fuel used for the first station is Rawang coal, at $4.93 per ton. That, I gather from the equivalent at the beginning, works out to about 11s. 6d., a price per ton which will be regarded with envy by English power-station engineers. What I want to ask the authors is: What is the calorific value of this coal, and what is the load factor on the station? The other question I want to ask is whether any other form of power, such as suction gas, is used in some of these smaller mines, and, if so, how that compares with the cost of fuel oil burned in Diesel or crude oil engines.

Mr. J. R. Cowie: There are one or two things which I have noted in regard to the paper; for instance, that the grouping of the costs excludes the capital costs. That does not happen in the Colonies only; it happens in places nearer home. What interested me was that some of my friends who are civil engineers and who have done work in many parts of the world tell me that Chinese labour is one of the most difficult forms of labour to put machinery against; that is to say, the authors have to justify their machinery against hand labour in some cases. The quantity, of course, and the question of hydraulics and working in water, limit the use of that labour, but there must be very many propositions in regard to these tin mines where the hand labour of Chinese coolies is a tough thing to get over because of the high capital cost of machinery. On page 185 I notice that fuses were used for protecting high-voltage lines. That has been done, I believe, in America with carbon tetrachloride fuses, but I cannot say with what success, as I have had no actual experience. I know, however, that the article has been manufactured in this country. Personally, I like the switch which the authors suggest. The next thing that interested me was what the authors had to say with regard to insects. On two occasions insects have been the cause of the blowing up of switchboards in mines in our country, and I know of some other cases where rats have been the cause of the same thing. The insects that worry me most are ants, not only because they get into all the crevices but because they eat the rubber cable. I should like to know what precautions the authors take against that sort of thing. On page 185 voltages are mentioned. There are a great many voltages there on direct-current work. Would it be possible to get a standard of two, and on alternating-current work a standard of three, that is to say, to allow 110 volts for lighting because of the water difficulty? I presume that the reason why so many accidents occur on the alternating-current work is because of the water difficulty. With regard to impregnation of coils do the authors really mean that, with an impregnated coil for high-tension work, 2,200 volts is the limit which is permissible? With reference to the question of variable speed on alternating-current motors, I saw in the Key Industries Exhibition in Glasgow a very interesting piece of apparatus. It was an hydraulic—oil variable-speed gear for coupling to alternating-current motors. This gear could vary from full speed one way right down to nothing, and right up the other way to full speed. The efficiency, I am sorry to say, was only about 80 per cent, but it was a very valuable gear and I hope to use it in many places. With regard to transformer oil, this is a question of taking chemical analyses and electrical tests. One should buy the very best quality that one can. In my city we test every transformer once in six months for sludging. We also test the quality of the oil—that is, an electrical test on the oil—every 12 months.

Mr. W. Lang: On page 171 there is a very interesting note regarding certificates which have to be obtained by those seeking appointments for the control of the electrical undertakings. I presume that that applies more particularly to Europeans, and that Chinese are not considered at all in undertaking such work. It is, I think, a very great compliment to the Institution to note that the Associate Membership class of the Institution is accepted without any further question, and I feel sure the President will join me in hoping that the time is not far distant when the various grades of the Institution will be recognized in this country before a position of even relatively minor importance will be granted. With regard to the Table of costs on page 172, I have had some little difficulty in understanding what these figures under "Cost per Unit Generated" really represent; that is to say, what kind of money is intended to be understood there? I think a little note to that effect would assist those studying the Table. Under "Various Data" I notice that there is an expenditure of 9·1 lb. of fuel per unit with an extended note of 6 lb. per unit. There are some stations in this country, working under very much better conditions, which are higher than that, and I should think it is quite a compliment to the way in which these stations are operated to find that there are such comparatively low figures as those. On page 185 the author refers to the moisture-laden atmosphere and suggests that a limitation of 2,200 volts should be adhered to in operating high-pressure electrical plant. It is somewhat surprising to me to find that the authors recommend a specification for those cables for wiring up the motors to the low-tension switchboard, and I wonder whether they have forgotten, or whether it is intended, that these cables should be impregnated. There is no mention of impregnation of the cables in the specification, neither is there any mention of lead sheathing. I take it that the authors had in view what is sometimes referred to as the leadless cable, but even with a leadless cable the importance of impregnating the core is quite patent to the ordinary cable user in this country, let alone in a country which is so laden with moisture as is the Federated Malay States. Such a cable as is described here I am certain could not stand 2,200 volts or even 500 volts for any length of time with security. The cable connecting the dredge to the shore described in the Bentong mine is very interesting. Whoever suggested the floating of the cable on barrels from the shore to the dredge is a very clever engineer. It has been the salvation of that cable. But it is rather surprising to find that the cable has not been further protected by the serving of jute or hemp or even by the protection of the usual strong Hessian tapes, which would lengthen its life very considerably. In addition to that, under conditions of that kind, if the authors would recommend their friends to paint the cable with

a bitumen paint periodically, they would get a very much longer and better life. I should also like to support a previous speaker with regard to the cable described on page 188, where a three-core cable is recommended to be run in pipes along the framing of the dredge. I am sure the authors would find that a three-core cable armoured would not cost very much more and would be a much more satisfactory job.

Mr. J. C. Wigham: There are one or two points about which I should like to ask a few questions. Could the authors give us the proportion of the water power to steam or oil power used in these mines? It would be interesting to know where most of the machinery has come from—whether it has come from this country or from America, both the electrical and the mining machinery. The cost per unit seems too good to be true. It is only a fraction over ½d. per unit for the total costs. Have we got those figures strictly correct? As I work it out it is only an expenditure of £750 for running the power station for a year, exclusive of coal, and, although the wages paid to the Chinese are very small, the cost of rewinding a single armature would run to a large figure in that part of the world. The efficiency of the water elevator is only 16·58 per cent. That is extraordinarily low as compared with the efficiency of lifting the same quantity of dirt or gravel by an ordinary lift or by trucks running on rails. I should like to know whether it is not possible to treat the tin in the bottom of the quarries and lift only the treated tin to the top, instead of lifting the whole of the tin, gravel and water. The load factor of the plant running the dredger seems extraordinarily high over a year, because there comes a time when the dredger moorings, etc., have to be shifted, and quite considerable intervals occur between the time it is tackling one portion of the gravel and the next.

Mr. W. S. Lonsdale (*communicated*): The paragraph which appeals to me most in Part 1 of the paper is the statement that mines under Chinese management in 1918 produced about 70 per cent of the total output of tin, less than half-a-dozen of these mines being electrically driven. With the information that we now have before us, I agree with the authors that there should be great scope for the electrical engineer in the immediate future. With regard to Tables 1 and 2, I notice that the figures cover a period of only three years, viz. 1917 to 1919. These figures might be misleading as they are based on advantageous years, when all the mines were working presumably up to their full capacity owing to the great demand for tin for munition work. I notice a reference in these tables to the use of Rawang coal, which in 1917 cost somewhere about 11s. 6d. per ton delivered. I should be interested to hear what is the present cost of this coal and also its calorific value. I agree with the authors that it is most important that all main switchboards in the power house should include instruments for measuring the output, or in other words a "summation" panel. Regarding the use of electricity, steam and gas in the same mine, I do not see any great necessity for this, even although winch and puddler loads are very fluctuating, since with a robustly designed a.c. or d.c. motor driven by belt with good flywheel effects this class of load should not present insuperable difficulties. In regard to the question of generation in bulk, I am quite in agreement with the authors as to the obvious difficulties, chiefly owing to the tin-bearing areas being worked out so rapidly. I cannot find any information in the paper as to what variation up and down from the normal speed is required by a gravel pump. The use of rotor resistances for three-phase motors is of course extremely wasteful in current, particularly as I notice that most of the motors are for 100 b.h.p. and over. I shall be interested to hear whether three-phase squirrel-cage motors with auto-transformers and regulators have been tried for this class of work. As the gravel-pump load seems to form a considerable proportion of the total load, and as one can obtain a very fine speed variation by shunt regulation, this class of work seems to point directly to variable-speed d.c. motors. In Part 2 of the paper I am rather surprised to notice two 450-kw. alternators driven by Pelton wheels, generating three-phase current at 400 volts, the pressure being stepped up to 3,000 volts for a 1½ mile transmission, and then stepped down again at the mine end. Why not generate at, say, 3,000 volts direct, as is done at the French Kampar mine, as described on page 181, where units at less than half this output are generating current at 6,000 volts? One of the most interesting descriptions in the paper is that of the suction-dredge plant at the French Kampar mine. This installation seems to have been very carefully worked out to suit the particular local conditions. I note on page 185 that the authors consider it inadvisable to generate at higher pressure than 2,000 volts, and I am rather interested to know what arrangements are made locally for repairs to high-tension windings, in view of the absence of skilled labour and difficulties in connection with stove-drying the windings on repair. Regarding the temperature-rise figures suggested for generators and motors, I do not understand why the authors should suggest a different standard for these two classes of machinery, differing only by 7 degrees F. From experience I myself have had in the Federated Malay States, I have not noticed that any trouble has arisen with machinery which has been designed for a standard temperature rise of 40 degrees C. (72 degrees F.) provided special tropical insulation is used, that is mica in place of press-spahn, and brass or bronze brush-holders in place of steel. I also found it most important that all brush springs should be made of phosphor bronze and not steel, as the rapid rusting of steel springs causes them to fa l a very few weeks after the machinery has been installed.

Mr. W. J. Wayte (*in reply*): Mr. Patchell comments upon the decreasing output of tin from the Federated Malay States. This is entirely due to the rich deposits becoming exhausted. The efficiency of tin recovery is dependent upon the nature of ground under treatment; with sandy ground the efficiency would be as high as 90 per cent, and less where the ground is of a stiff or clayey nature. The fineness of the tin is also a large factor affecting recovery; with puddling plants slimes are inevitable and the sluice boxes are designed to give efficient recovery. Without referring to the East I regret I am unable to say exactly how many mines are using

electric power. As regards the question of wayleaves for transmission lines, the power company receives no assistance from the Government in procuring wayleaves, and as most of the land is either tin bearing or planted with rubber, the supplier of power may be at the mercy of the land-owner; assistance from the Government in this respect would remove a large difficulty to the power supplier. The nozzle pump used on suction dredges is of the ordinary centrifugal type, but as the water used is often of a slimy nature the efficiency would be lower. In practice it is found that the power required for driving the nozzle pump is approximately the same as for driving the gravel pump; for instance, an 8-in. gravel pump, lifting 16,000 cubic yards of solid per month to a height of 70 feet, would require motors of 80 b.h.p. for each pump. The monitor pressure required for breaking down ground depends upon the nature of the ground under treatment. Hard clay will require as much as 180 lb. pressure, whereas ground of a friable gravelly nature can be washed down with a pressure of 20 to 40 lb. With reference to bucket dredges and Table 5, the power taken by the bucket chain, ladder winch, and mooring winches is intermittent and the motors are usually very liberally rated, and the pressure pumps and screen are always running at practically constant load. The tin is washed up with water on the tables of the dredge exactly in the same way as that described for open cast mines, and very little further washing is necessary. The high-pressure pump supplies water at a pressure inside the screen to break up any large hard lumps which would otherwise be lost, the pressure required of course depending upon the nature of the ground.

Mr. Patchell asks for further information with regard to the climatic conditions. The average rainfall in the Kinta Valley is 99 inches; at Taiping Hill, 5,000 feet above sea level, the average rainfall is 240 inches. In the Kinta Valley the average maximum shade temperature is 91° F.; average minimum shade temperature 70° F.; humidity 77 per cent; mean dry bulb 82·29°; mean wet bulb 76·49°; height above sea level approximately 130 feet.

The haulage speed is usually about 6 miles per hour.

Mr. Llewellyn Foster gave some interesting data regarding gravel pumps as used for working China clay in Cornwall, and I was surprised to hear that the pump was only capable of dealing with lumps which would pass through a $\frac{1}{2}$-inch mesh. The pumps used in the F.M.S. are frequently run with a suction head of 15–20 feet, and anything which will pass through the suction nozzle will be taken up and discharged by the pump. The bearing which gives most trouble is the water-sealed four-part bearing which supports the overhung impeller. This bearing is sealed by water at a pressure of about 15 lb. per square inch to prevent any leakage of air into the pump, and if clear water is used for the purpose very little trouble is experienced. The difference in the units used per yard treated by the first two mines in Tables 1 and 2 and the first two in Table 3 is explained by the fact that the former are open cast mines where a considerable amount of pumping is always necessary, whilst the latter are respectively dredging and lode propositions. Bucket dredges aim at continuous operation and only stop when repairs are necessary. With reference to the permissible temperatures of generators and motors, if moulded mica insulation is used for the slot and the coil is carefully impregnated I do not think a final temperature of 158° F. should be dangerous, but it would probably be difficult to remove a coil without damage after working for considerable periods at high temperatures. Practically no trouble has been experienced with oil-filled transformers. With reference to fatalities on lighting circuits (page 187) the authors wished to emphasize the danger to life with alternating currents even at low potentials. The cost of transport of tin is paid by the smelter who usually takes delivery at the miner's godown.

In reply to Mr. Couzens the calorific value of the coal known as Rawang "smalls" is 8,500–9,000 therms per lb. Suction-gas engines are frequently used on the smaller mines, and running costs compare favourably with Diesel or crude oil engines.

Mr. Cowie criticizes the voltages recommended. It is pointed out in the paper that 230 volts is generally used for lighting. The variable-speed gear for alternating-current motors mentioned by Mr. Cowie is very interesting, and I should like to have more information concerning this apparatus.

Mr. Lang will find, if he refers to the specification of the dredge shore cable on page 188, that the authors have recommended a protective compounded braiding over the armouring; and it is intended that the dredge cables should be impregnated. With reference to Table 1, the cost per unit generated is in cents.

In reply to Mr. Wigham I regret I have no figures of the proportion of water-driven machinery to that of other power. With the exception of the French mines, practically all electrical and mining machinery is manufactured in England. The cost per unit in the Tables includes the cost of repairs to generating plant but not motors on the mines.

In reply to Mr. Lonsdale I do not think the figures given in Tables 1 and 2 are misleading. Owing to the decrease in the value of deposits all mines have been working at their maximum output for many years. The price of Rawang coal is now practically double the cost in 1917. I agree with Mr. Lonsdale that there is no reason why winches and puddlers should not be driven electrically. Squirrel-cage rotors with auto-transformers and regulators have not been tried for variable-speed work, and I am doubtful if this class of motor would give the fine regulation which is essential for gravel pumps. I am afraid the cost of the plant and low efficiency of conversion would prohibit the use of direct current, otherwise direct-current motors would be ideal. With reference to Idris mine, when the plant was first designed it was intended to take half the power to a mine situated $3\frac{1}{2}$ miles from the power station; for this reason and to prevent trouble from lightning it was decided to install transformers. Repairs to high-tension windings are generally carried out by the mine staffs with native labour.

PROCEEDINGS OF THE INSTITUTION.

4TH WIRELESS SECTIONAL MEETING, 19 NOVEMBER, 1919.

(Held at the Institution of Civil Engineers.)

MR. ROGER T. SMITH, President, took the chair at 6 p.m.

A paper by Professor C. L. Fortescue, Member, entitled "The Design of Multiple-Stage Amplifiers using Three-Electrode Thermionic Valves" (see page 65), was read and discussed and the meeting adjourned at 7.50 p.m.

640TH ORDINARY MEETING, 11 DECEMBER, 1919.

(Held at the Institution of Civil Engineers.)

Mr. ROGER T. SMITH, President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting of the 27th November, 1919, were taken as read, and were confirmed and signed.

The President announced that the Council had elected Professor Hendrik Antoon Lorentz, of Leyden University, an Honorary Member of the Institution.

A list of candidates for election and transfer approved by the Council for ballot was taken as read and was ordered to be suspended in the Hall.

A paper by Captain J. M. Scott-Maxwell, B.Sc., Member, entitled "Scientific Works Management: A Solution of the Capital and Labour Problem," was read and discussed and the meeting adjourned at 7.45 p.m.

5TH WIRELESS SECTIONAL MEETING, 17 DECEMBER, 1919.

(Held at the Institution of Civil Engineers.)

Dr. W. H. ECCLES, Chairman of the Wireless Sectional Meetings Committee, took the chair at 6 p.m.

A paper by Professor G. W. O. Howe, D.Sc., Member, entitled "The High Frequency Resistance of Wires and Coils" (see page 152), was read and discussed and the meeting adjourned at 7.35 p.m.

641ST ORDINARY MEETING, 18 DECEMBER, 1919.

(Held at the Institution of Civil Engineers.)

Mr. ROGER T. SMITH, President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting of the 11th December, 1919, were taken as read, and were confirmed and signed.

Messrs. P. W. Snelus and R. K. Keer were appointed scrutineers of the ballot for the election and transfer of members and, at the end of the meeting, the result of the ballot was declared as follows:—

ELECTIONS.

Member.

Langdon-Davies, Walter.

Associate Members.

Brander, George.
Davenport, Arthur.
Evans, Bertram Augustus.
Hoppell, Arthur Samuel.
Horne, Arthur Stephen.
MacLean, Archibald Barr, M.A., B.Sc.
Roberts, Arthur John.
Sharp, Guy Descarrieres, Lieut.-Commdr., R.N.
Small, William Charles.
Smith, John.
Stevenson, Horace Alexander.
Talbot, William Ernest.
Turner, Frank Cuthbert, B.Eng.
Youngmark, Frederick Albin.

Graduates.

Atkinson, James William.
Garnes, John Christie.
Gazard, William Albert.
Hadrill, Harold John.
Townend, Wilfred Thomas, Eng.-Lieut., R.N.

Associate.

Westlake, George Frederick.

TRANSFERS.

Associate Member to Member.

Bilsland, John.
Milnes, George Clement, M.C.

Graduate to Associate Member.

Bedford, Alphonse Levi.
Mitchell, Raymond James.

Student to Graduate.

England, Maurice Ord F.
Platt, Claude Bernard M., M.B.E.

A paper by Messrs. D. M. W. Hutchison, B.Sc., Member, and W. J. Wayte, Associate Member, entitled "Electricity in Tin Mining (see page 171), was read and discussed and the meeting adjourned at 7.45 p.m.

642ND ORDINARY MEETING, 8 JANUARY, 1920.

(Held at the Institution of Civil Engineers.)

Mr. ROGER T. SMITH, President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting of the 18th December, 1919, were taken as read, and were confirmed and signed.

A paper by J. Shepherd, Member, entitled "Failures of Turbo-Generators and Suggestions for Improvements" (see page 125), was read and discussed and the meeting adjourned at 7.50 p.m.

6TH WIRELESS SECTIONAL MEETING, 14 JANUARY, 1920.

(Held at the Institution of Civil Engineers.)

Dr. W. H. ECCLES took the chair at 6 p.m.

The minutes of the Wireless Sectional Meeting of the 17th December, 1919, were taken as read, and were confirmed and signed.

A paper by Captain H. J. Round entitled "Direction and Position Finding" was read and discussed and the meeting adjourned at 8 p.m.

643RD ORDINARY MEETING, 22 JANUARY, 1920.

(Held at the Institution of Civil Engineers.)

Mr. ROGER T. SMITH, President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting of the 8th January, 1920, were taken as read, and were confirmed and signed.

A list of candidates for election and transfer approved by the Council for ballot was taken as read and was ordered to be suspended in the Hall.

Messrs. C. S. Buyers and L. J. Rouard were appointed scrutineers of the ballot for the election and transfer of members and, at the end of the meeting, the result of the ballot was declared as follows:—

ELECTIONS.

Member.

Lulofs, Warner, D. Ing.

Associate Members.

Arthur, James William.
Beall, Harold John.
Binns, Arthur Priestley, B.Sc.
Bound, Arthur Frank
Coe, Gordon Douglas.
Crofts, Cecil Burnell, B.Sc. (Eng.).
Darling, Henry John.
Dimmer, Leonard George.
Farrar, Fred
Farrar, Romilly Rooth.
Ferguson, George Frame.
Fuller, L. O.
Gillman, Ernest Percival.
Halton, Edward.
Hedley, John.
Jack, Robert Gardner.
Jewell, William Edward.
Jull, Rowland Stanley.
Line, Richard.
MacLaren, John.
Mears, Thomas, B.Sc.
Moore, Walter Nicholas.
Palmer, James Brian.
Parrott, George Alexander.
Roberts, Harry Manley.
Stephens, John Grant.
Stubbings, George Wilfred.
Sutton, George Percy.
Thompson, Hugh John D.
Wamberg, Frederik Christian.
Watson, Henry Sinclair, B.A.
Watson, John Douglas.
Webb, William Lloyd.
Welch, John Guy Lawson.

Graduates.

Banerjee, Dhirendra Lall.
Bennett, John Ernest, B.A.
Blakeley, George Philip W.
Carnaby, Norman Edward.
Chien, Kao Chien, B.Sc.
Darby, John Francis.
Doyle, Lindsay Gordon.
Edwards, Arthur Rowland.
Ensor, Eric Lovell.
Evans, Clive Walter.
Ghose, Monindra Nath.
Griffiths, Henry Rae.

Graduates—continued.

le Conteur, Louis, Capt., R.G.L.I.
Luffingham, Laurence John.
McGowan, George.
McLean, Donald.
Mitchell, Thomas Alfred.
Newport-Dunster, Basil.
Nimmo, Adam Arthur.
Page, John Joseph.
Ray, Ramapati.
Roberts, Sarah Evans (Miss).
Smith, Esmond Wassell.
Smith, John Albert
Walker, James Smith.
Walton, James Rignell.
Wyatt, Reginald Albion.

Students.

Allsop, Charles.
Anderson, David Stirling.
Anderson, James.
Arman, Adrian Neville.
Askwith, Edward Douglas.
Baggs, John.
Baker, John Henry.
Baldwin, Lewis Leon.
Barraclough, Alfred.
Belcher, Arthur Jackson.
Benger, William Alan.
Bentall, Pendril John.
Bird, Reginald Thomas.
Bishop, Herbert Leonard G.
Booker, William Mason.
Brookes, Arthur Edwin.
Budgett, Felix La Tourette.
Bunyan, John.
Burt, Brian Morton.
Butten, Ernest Edward.
Carnegie, James.
Carr, Conway Buxton.
Casson, William.
Chamberlain, Eric Lawrence R.
Chapple, Harry John B.
Clark, Leonard Jack.
Clutterbuck, Thomas.
Coe, Reginald Thornton.
Collier, Harold.
Cook, James Chartres.
Cook, Robert.
Cook, Walter Kitchener.
Corrans, Robert.
Damsell, Raymond Frederic.
Dixon, Arthur, B.Sc. (Eng.).
Dodsworth, Thomas Hessler.
Donnelly, Wilfrid.
Dunlop, Robert Paterson.
Edgley, George W.
Edmunds, Thomas Martin.
Elliott, Maurice Gilbert R.
Falk, Geoffrey Ferdinand.
Farrell, James Fraser E.
Fearnley, Bertie Ernest.
Ferguson, Alexander Dalgety.
Field, Charles Edgar.
Filbey, Charles Albert.
Firnberg, Leopold Bernard.
Francis, José Ronald.
Fuchs, Arnold.
Gerrard, Dudley Carlton.
Gerry, Godfrey Cecil B.
Ghosh, Jagabandhu.
Goodwin, Ralph.
Graham, Charles Parnley.
Graves, Frederick Walter.
Greer, Stewart Peddie.
Grepe, Frederick Yorke.

Students—continued

Griffiths, John Balmain.
Grimston, Robert Villiers.
Grocott, Gilbert Henry.
Hall, William Samuel H.
Hampson, William Percival.
Harding, Horace Ralph.
Harle, James Alfred.
Harley, Laurence Shepheard.
Harlow, Harold George.
Harrison, Douglas William.
Hedley, William Ernest.
Heinrich, Arthur Frederick.
Herriot, David Robertson.
Hirst, Allan William.
Holister, Stanley Walter.
Hollyman, Robert Henry.
Hook, Herbert James.
Hopkins, Ronald Edwin.
Hutchings, Philip Townshend.
Ivey, Ewart Godfrey.
Jackson, John William.
Jeffries, Robert Ernest.
Jenkins, William Arthur.
Johnson, James Ralph, B.Eng.
Jolin, Charles Henry.
Jones, Frank Leslie.
Jones, Harold Lancaster.
Kirkman, Douglas William T.
Knight, Sidney Alfred.
Laing, John Wallace.
Lakey, Eric Harold.
Latimer, Kenneth Eric.
Leech, Leonard.
Littler, Herbert A.
Logan, Edward Alexander.
Longbottom, Jack.
Lovell, Fred.
McJannet, David William.
Mackay, William Morton.
McLaren, John.
Maclean, James Adam.
McQuillan, Cecil.
Mann, Reginald William.
Marten, Ernest William.
Martin, John.
Melling, Cecil Thomas.
Miller, Frederick McKenzie.
Milner, Harry.
Molle, George William.
Moody, Harold Sydney.
Morgan, Ivor.
Nuttall, Edgar Moorhouse.
Palfrey, Harry James D.
Phillips, John Douglas N.
Pilkington, Denis Fielden.
Piquet, John.
Plummer, Reginald.
Pointon, Herbert Vincent.
Pollott, William.
Poole, Leslie Richard W.
Price, Francis Ernest.
Puckle, Owen Standidge.
Quilliam, Leslie.
Read, John Carley.
Rendell, Leonard Morey.
Rheam, George Turner T.
Riley, Colin.
Ringang, Rikzin Dorje.
Roberts, Edward James.
Roberts, Jack Fowler.
Rocks, Peter.
Sadler, Gilbert Vaughan.
Salzmann, Otto Malcolm, B.Sc. (Eng.).
Samuel, Harry Phineas.
Samuelson, Hugh Melvin.
Say, Maurice George.
Scroggie, Marcus Graham.
Shand, John Aberdour.
Sharp, Harry Steven N.
Sim, William.
Smith, Leslie Morgan.
Speirs, Hector McArthur.
Spence, Harold Cruickshank.
Springsguth, Charles Edward.
Stephenson, Robert Maxwell.
Stewart, Ian.
Strange, Frederick Philip O.
Taylor, Ernest George.
Taylor, Harold Edward.
Templeton, William.
Thomas, Walter Stanley.
Thompson, Cecil George.
Thompson, Frank.
Thomson, Harold Leslie.
Toms, William Harold.
Torry, Reginald Gordon.
Tovey, Maurice Herbert.
Trelease, John Stanley.
Turner, Eric.
Tustin, Arnold.
Vickers, Edward.
Waggott, William Norman.
Walker, Harry Barlow.
Warwick, Albert.
Watts, William Ewart.
Wells, John Spencer.
Westerhout, Cecil Gomes.
Williamson, Alexander Greenwood.
Wills, Felix Perceval.
Woodward, Charles Edward.

Associates.

Dennison, James Douglas.
Grier, John James.
MacIntyre, Hugh McCallum.
Ryan, Mervyn Frederick.

TRANSFERS.

Associate Member to Member.

Archibald, Robert Douglas.
Boyd, Arthur.
Bryans, Robert Henry.
Dyer, Charles Frederic.
Harrison, Norman, Lieut.-Col., C.M.G., D.S.O.
Haworth, Harold Firth, Ph.D.
Hogg, Patrick Mackintosh.
Horsley, James Arthur B.
MacGregor, William Duncan.
Teago, Frederick Jerrold, M.Sc.
Thorrowgood, William John.

Associate to Member.

Mayne, Robert Newell.

Graduate to Associate Member.

Aldridge, Arthur Peachey.
Midgley, Harry, B.Sc.
Smith, Walter Sydney B
Thomson, Douglas Gordon.
Wardle, Percy.
Wilson, Francis Joseph H.

Student to Associate Member.

Fisher, Francis William.
Marks, Ernest.
Mathias, Egerton Lloyd A.
Painton, Edgar Theodore.
Perrow, Frederick Alfred P

Associate to Associate Member.

Callander, John Campbell.
Millar, Hawthorne McKenzie.
Trusler, William Thomas.

Student to Graduate.

Dawes, Ronald Richard.
Harral, Richard Harold.
Leishman, George Alexander B.
Perrin, James Frederick.
Powell, Cuthbert Alban W., B. (Eng.).
Riley, Thomas Sharp, M.C
Ripley, Dunstan.
Romeira, Manoel Pinto.
Tapsell, Herbert James.
Trippe, Sidney Howard.
Vowell, Christopher.
Wall, Harold Henry.

The following donations were announced as having been received, and the thanks of the meeting were accorded to the donors :—

Building Fund.—M. Beales, G. H. Davies, A. H. Finlay, M. McA. Gillespie, S. E. Glendenning, J. S. Highfield, H. Hirst, Admiral of the Fleet Sir H. B. Jackson, G.C.B., W. McGeoch, Prof. J. T. MacGregor-Morris, M. Petry.

Library.—R. G. Allen, W. T. Anderson, P. R. Coursey, Dr. G. Kapp, R. Rankin, R. A. van Sandick, C. F. Wade, E. Bennis & Co., Ltd., The British Thomson-Houston Co., Ltd., Dominion Water Power Branch (Canada), The General Electric Co. (U.S.A.), Manchester Steam Users' Association, Massachusetts Institute of Technology, Post Office Engineering Department, Messrs. E. & F. N. Spon, Ltd., *Der Schweizerische Elektrotechnische Verein*, The Wireless Press, Ltd.

Benevolent Fund.—See *Institution Notes*, No. 18, page 12 February 1920.

A paper by Mr. J. L. Thompson, M.Sc., Associate Member, entitled "Transformers for Electric Furnaces," was read and discussed and the meeting adjourned at 7.40 p.m.

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TRANSFORMERS FOR ELECTRIC FURNACES.

By J. Lindley Thompson, M.Sc., Associate Member.

(*Paper received* 30 *October*, 1919; *read before* The Institution 22 *January*, *before the* North-Western Centre 27 *January*, *before the* North-Eastern Centre 9 *February*, *before the* Scottish Centre 10 *February*, *before the* South Midland Centre 25 *February*, *and before the* North Midland Centre 23 *March*, 1920.)

Since the first practical electric furnace was successfully manufactured by Stassano in 1898, there has been rapid progress made in this type of apparatus and its necessary auxiliaries.

It is the author's intention in this paper to deal with the chief piece of auxiliary apparatus used with electric furnaces, i.e. the static transformer.

The points to be dealt with are:—

Requirements for useful service.
Construction and electrical features.
Future requirements.
Design of large furnace transformers.
The ideal furnace transformer.
Mechanical stresses.
Furnace lay-out.
Cost and weight.

There are many types of electric furnaces in commercial use at the present time and they may be classified under four heads:—

(1) Arc furnace	..	Radiation type for steel.
(2) Arc furnace	..	Conduction type for steel.
(3) Induction type		For steel.
(4) Resistance type		For carbide, carborundum and ferro-silicon.

With furnaces under types (1), (2) and (4), transformers are nearly always required, while type (3) is in itself a static transformer. As is well known, the induction furnace consists of a closed magnetic laminated core around which the primary coil is wound, while the furnace bath forms around the core a secondary circuit complete or in part, the remaining portion of the circuit being wound round the core over the primary coils. Such a type is the Rochling Rodenhauser furnace. The only advantage that can be claimed for this type of furnace from an electrical standpoint is that no heavy low-tension alternating currents have to be catered for in long lengths of lead.

The disadvantages are:—

(*a* Low power factor due to the high reactance which is a necessity in this crude transformer.
(*b*) For a reasonable power factor to be obtained, a frequency of 5–25 is necessary, which in most cases means the additional expense of a frequency changer.

The induction furnace has not made much progress during the past 10 years, and as this country is almost entirely unfamiliar with its service conditions no further comment will be made.

Arc and Resistance Furnaces.

With both types of furnace, tranformers are in general use. The electrical characteristics of the transformers for the two types of furnace differ somewhat, but their construction is on similar lines. It was about 1910 that the electric furnace for steel manufacture began to occupy the minds of British engineers, and the transformers supplied for these early furnaces were built to the general specification of power transformers.

Transformers for use with furnaces have to be of substantial construction, due to the nature of the load they have to carry and the operation conditions under which they are to serve.

Various troubles were experienced with transformers built to early designs when put into operation, and they were briefly as follows:—

(1) Loss of low-pressure voltage across the arc due to bad lay-out of leads, or to reactance values of the transformers being too high.
(2) Failure of insulation of switchgear and transformer terminals on the high-pressure side due to the heavy auto-transformer effect in consequence of the large range of voltage.

(3) Mechanical damage to coils in the transformers due to frequent current-rushes.
(4) Unbalanced voltages on the low-pressure side of Scott-connected transformers due to unscientific design.
(5) Failure of transformers due to bad housing, unskilled operation, and heavy overloads.

With the experience of the past few years and a careful study of the conditions of service on site, the above causes of trouble have been practically eliminated, so that the furnace transformer can now be said to be thoroughly sound, both mechanically and electrically. Transformers for use with resistance furnaces, as defined by the author, have not caused so much trouble as those for steel furnaces, due to the more stable conditions of loading; but the accommodation of heavy currents, the insulation, housing and operating questions have led in this case also to more sound and reliable construction.

Since the steel furnace is that which is most common and causes most criticism, it is with transformers for this condition of service that the author mainly deals.

Transformers for Steel Furnaces.

The requirement of steel furnaces may be for single, two- or three-phase supply, but the general characteristics of the transformers are the same for all three.

Electrical Characteristics.

Voltage ratio.—Furnaces in general require a minimum of three low-tension pressures for use at different stages of production.

Reactance.—The transformers must be provided with a certain amount of reactance for steadying the arc and reducing the rush of current to safe values in the transformer windings and supply mains. This reactance may be internal or external, depending on the size of unit, and its value is dependent on the lay-out of the low-pressure leads, the furnace construction, and the supply company's capability of dealing with sudden and heavy loads.

End turns.—It is necessary to reinforce heavily the end turns of the high-pressure windings, due to the possible high-pressure rises consequent on heavy current-rushes; also extra insulation between the remaining turns is advisable, especially where tappings are brought out.

Tappings.—The tappings for voltage variation should be on the high-pressure side, for due to the few turns on the low-pressure side correct voltages cannot readily be obtained.

The switchgear problem is also simplified by the use of high-pressure tappings.

The tappings should be in the middle of the winding, to eliminate high voltages by auto-transformer effect and also to free the reinforced turns from any break in their insulation.

Ratio of iron to copper loss.—The ratio of iron to copper loss is not important, as the transformers are never run for any length of time on open circuit. The total losses should be a minimum at the most common voltage.

Circulating currents.—Coils connected in parallel should be so placed that they are equally loaded under all conditions of service.

Mechanical and Constructional Requirements

Robustness.—The transformer must be of sound mechanical construction with its coils rigidly supported in all directions in which movement is possible under a heavy rush of current.

The major force in a sandwich-type winding is axial, and a minor force in a radial direction due to coil dimensions.

With a concentric type of winding, these forces are reversed.

Bracing to avoid destruction of windings due to a fault between turns is not a practical possibility, as all the power of the supply system would tend to rush to such a fault and destruction would result whatever bracing be provided.

Cleating of leads.—All leads, high and low pressure, should be securely clamped to prevent movement due to heavy current-rushes.

This clamping is very necessary for low-pressure leads carrying heavy current, as they tend to vibrate and chafe the insulation between them.

Insulation.—The insulating material should be strong and firmly held in position, being assembled with the coils and secured while under pressure.

Ventilating ducts.—Numerous ventilating ducts should be provided by means of suitably arranged spacing blocks between the several coils to prevent local heating. These ducts should ensure a free and ample circulation of the cooling medium.

High-pressure terminals.—Only the high-pressure leads required should be brought out of the case, the remainder being retained under oil level. The high-pressure line leads should be brought through individual insulators.

Low-pressure leads.—The low-pressure leads should be increased in section, from two or three inches under oil level, to prevent heating.

Location and Operation.

Self-cooled transformers should be placed in well-ventilated chambers with a minimum distance between them of 18 inches for sizes up to 1,000 k.v.a. and 24 inches for large units.

They should be kept clean and easy of access.

They should be placed as near to the furnace as possible and symmetrical, with a fireproof barrier between them and the furnace.

The operation should be supervised by a skilled attendant, as unskilled attention has been the cause of serious trouble.

The low-pressure leads should be as near together as possible, and interleaved for currents higher than 5,000 amperes.

The foregoing general requirements are the result of several years' experience gathered in the design, manufacture and operation of furnace transformers.

Core and Shell Type of Construction.

Transformers for furnace work are manufactured of both the core and shell type constructions.

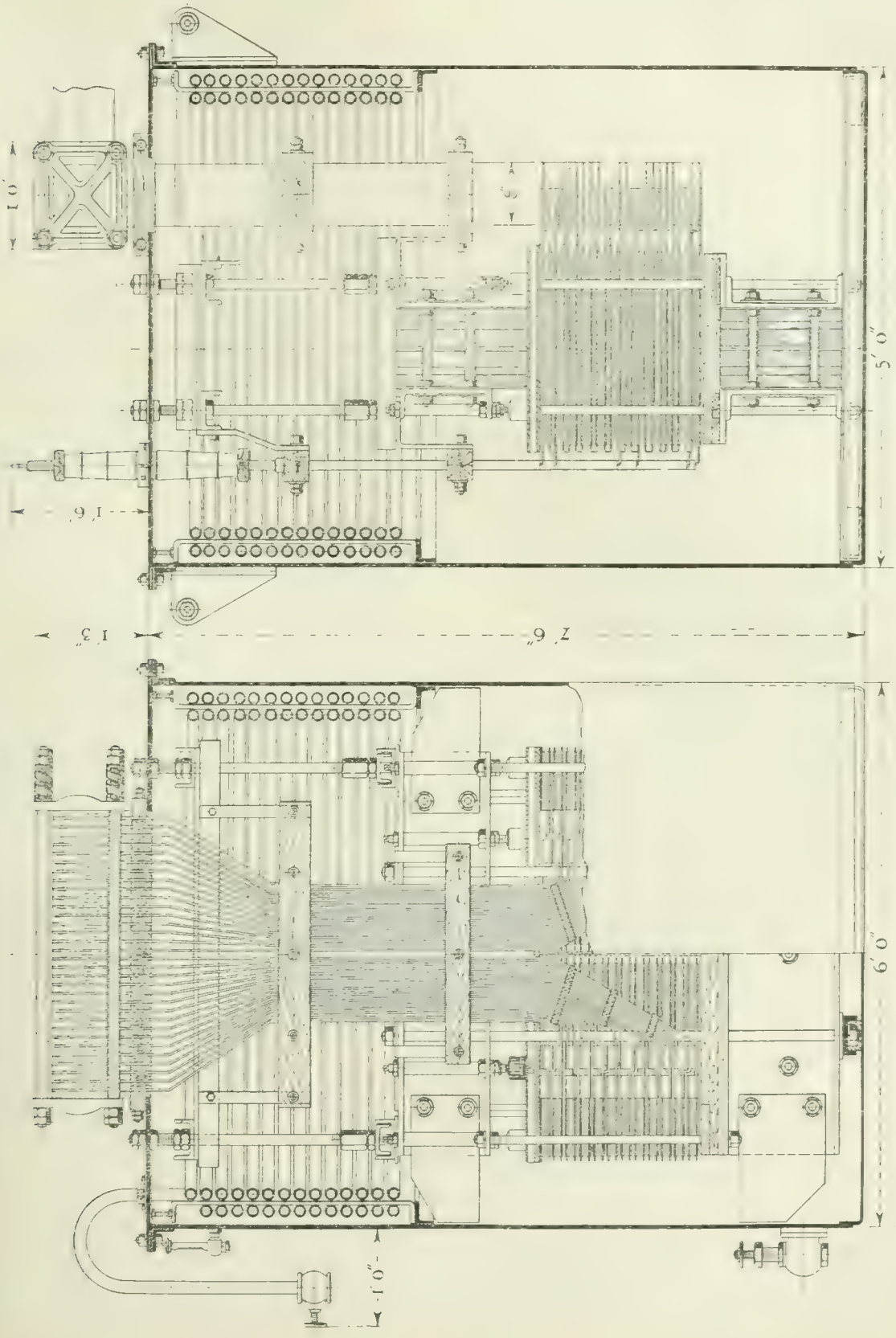

FIG. 1.—1,250-k.v.a. single-phase core-type furnace transformer.

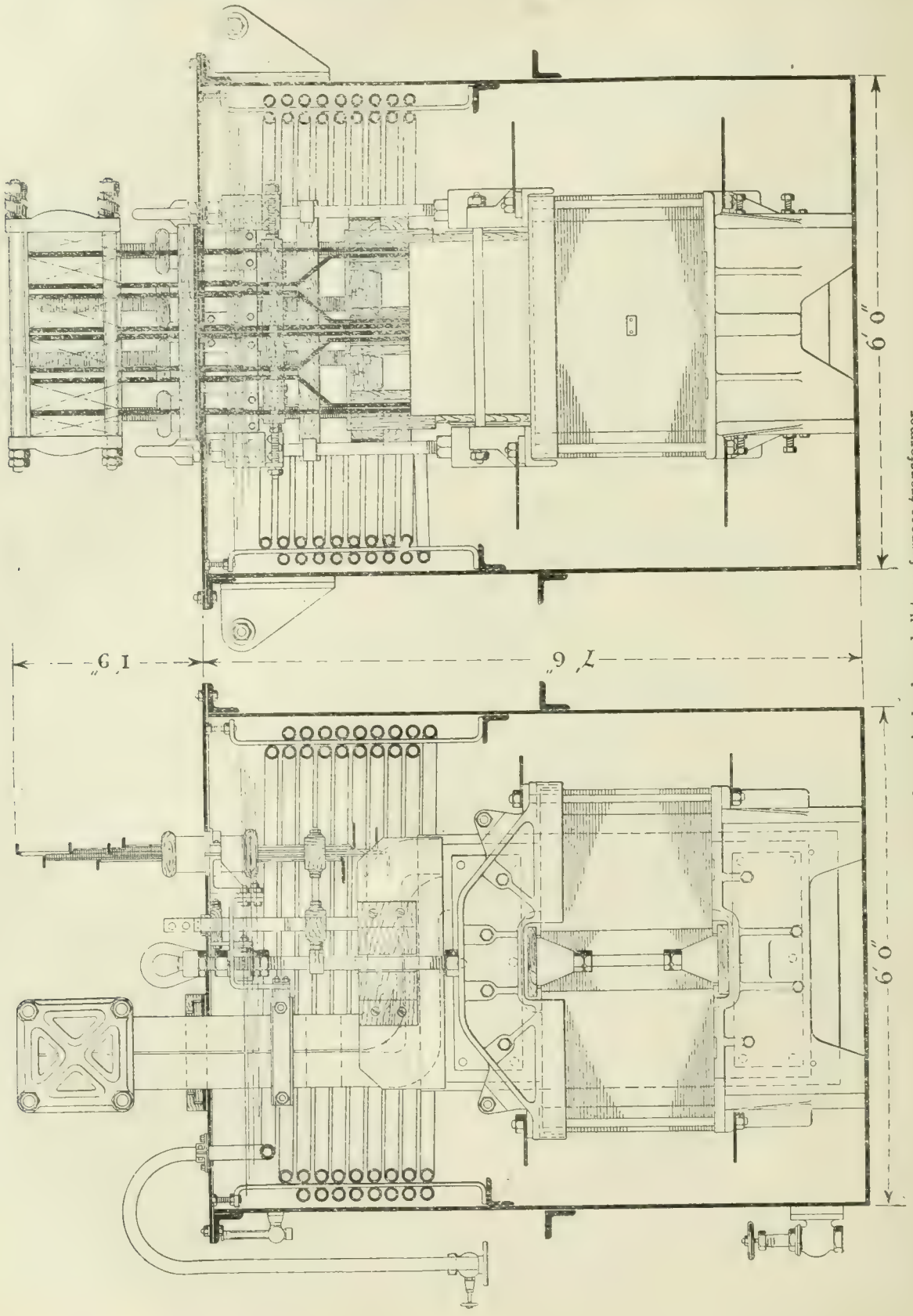

FIG. 2.—1,250-k.v.a. single-phase shell-type furnace transformer.

Figs. 1 and 2 show typical examples of both types. Both types have been satisfactorily manufactured and are giving good service, but a comparison of the two methods will be of interest.

Core type (*Fig.* 1).—The core-type construction in general has its coils in sandwich form, to admit of easy access to both low and high-pressure coils and leads, and also to admit in the design of the required reactance being obtained. The core is built up in a rigid manner similar to a standard power transformer, and the coils are assembled on the core one by one and insulated in an approved manner.

The low-pressure and high-pressure leads are brought out on opposite side of the core to facilitate mounting.

The low-pressure coils are connected in parallel or in series parallel to obtain the required current-carrying capacity.

The low-pressure leads are brought out as close together as possible in an interleaved fashion to reduce the reactance to a minimum.

A strong and good-looking piece of apparatus can be made with this construction, provided good workmanship is available.

There are few comments on this type which might be of interest.

Advantages.—The coils are almost wholly visible and there is no congestion of leads as the whole face of the two sides of the transformer winding is available.

The relative economic proportions of actual material, i.e. copper to iron, can be reasonably obtained.

Disadvantages.—On account of the number of low-pressure coils in parallel and the unequal length of their leads, a true distribution of current is difficult to obtain.

The coils surrounding the core are liable to damage during manufacture and shipment.

There are many heavy joints of copper on the low-pressure side, and the failure of any one may cause serious trouble.

There is always a shrinkage of insulation due to the weight of the coils acting directly, and hence some means of compensating for this shrinkage is necessary.

In a sandwich core-type winding the ventilating ducts are in a radial direction and at right angles to the natural flow of oil, and hence are of very little use for the purpose for which they are intended. The losses when under load are very heavy, due to part of the leakage flux between the primary and secondary windings cutting the core clamping plates and punchings at right angles on two sides of the core (see Fig. 3).

If the number of primary and secondary groups is large and voltage variation is required by means of high-pressure tappings, then the load distribution in the low-pressure windings is likely to be disturbed. The low-pressure coils adjacent to the cut-out high-pressure coils will carry little or no load owing to their increased reactance.

This unequal loading is a great disadvantage, especially if a constant low-pressure current at each voltage is required

Shell type .(*Fig.* 2).—The furnace transformer built on the rectangular shell-type principle has its coils arranged in a sandwich fashion, similar to a standard power transformer.

The coils are wound in sections and assembled together with their requisite insulation under pressure.

Numerous and large ventilating ducts are provided between each coil or pair of coils.

The low-pressure coils are usually wound of bare heavy copper strips on edge, and the turns so disposed as to reduce the circulating currents to a minimum.

The individual turns of the low-pressure coils are left bare, but insulated from one another by solid insulating channels and barriers. The completed windings are fitted with their internal coil supports and placed in their base castings, the punchings being built around them to the required height.

Coil supports are provided internally in a radia direction, to stiffen the coils and prevent their weight

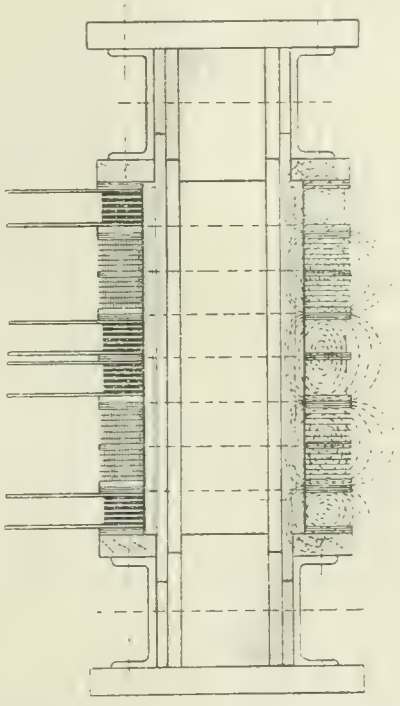

FIG. 3.—Section of a core-type furnace transformer, showing leakage fields and section of coils and insulation.

being carried by the punchings. The coil heads are also supported each side, top and bottom, in an axial direction.

The low- and high-pressure leads are brought straight up from the top of the coils through stiff cleats.

The high-pressure coils are generally all in series with the tappings in the centre of the windings, so as not to interfere with the reinforced turns or materially affect the balance of load in the low-pressure parallel coils.

The low-pressure leads are brought out with heavy copper bars of increased section to eliminate heating above the cooling medium.

There are also a few comments on this type of apparatus which might be of interest.

Advantages.—The coils are protected from mechanical

damage during manufacture and shipment by the core and castings.

All ventilating ducts are in a vertical direction in the line of flow of the cooling medium.

The copper forming the low-pressure coils and leads may be of one length, thus obviating heavy joints inside the transformer case.

The low-pressure leads are all of equal length.

The central position of the high-pressure tappings reduces to a minimum the unbalancing of the load in the low-pressure coils.

The copper loss is not greatly in excess of the $I^2 R$ loss, since the leakage flux cuts the punchings in a parallel direction, except at the coil heads, but here the leakage flux is of low magnitude due to the longer leakage path and the greater distance of the iron circuit from the coils (see Fig. 4).

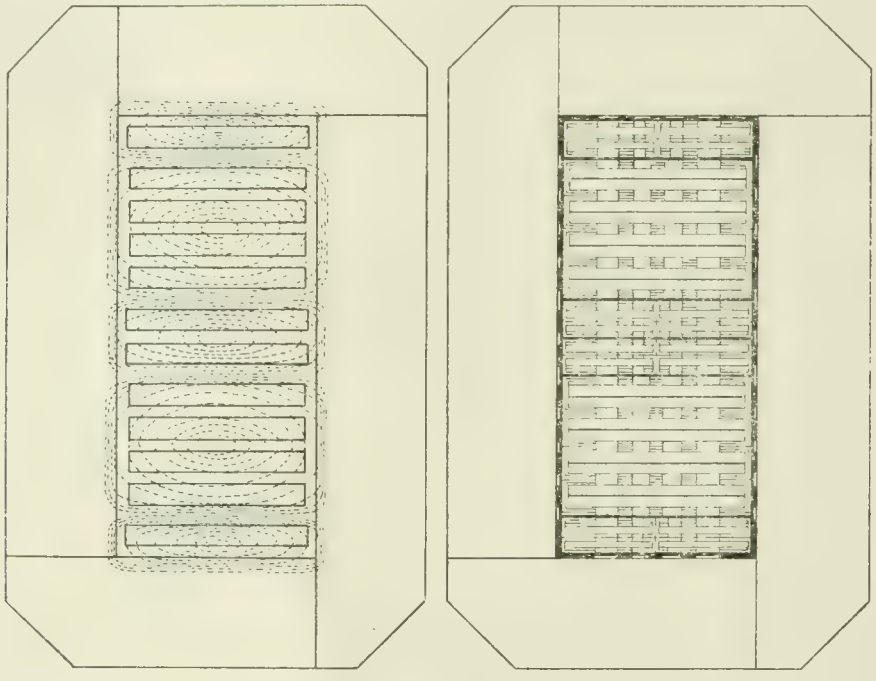

FIG. 4.—Section of a shell-type transformer, showing leakage fields and method of coil insulation.

Disadvantages.—The coils are not wholly in view, but the coil heads are visible unless covered by unnecessary clamps.

The high and low-pressure leads coming out from the same end of the windings give a congested appearance and, if not properly arranged, may cross one another too closely and in time cause a fault.

The economical proportions of active material cannot be so readily obtained as in a core-type transformer. This is because the iron section of a shell-type transformer is usually much larger than that of a core type for the same rating, and hence fewer turns are required to induce the required voltage.

This difficulty is more pronounced in large sizes, but can in a measure be remedied by designing on the lines of the author's patent No. 131,026, which will be referred to later

FUTURE REQUIREMENTS.

Having described the requirements of a furnace transformer and the two general types of manufacture, it is now intended to view the future requirements of furnace manufacturers and their effect on the present manufacture.

Up to the present time, electric steel furnaces have been designed and built for dealing with quantities up to about 15 tons, but the future will demand larger sizes up to 30 or 40 tons' capacity.

Taking the kilovolt-amperes required per ton at 200, then transformer groups of 6,000 to 8,000 k.v.a. will be required.

The problem of transforming this amount of power is not unreasonable, since power transformers for dealing with much larger capacities have been manufactured.

The solution of this problem is not so simple, due to the low voltages required and the consequence heavy currents.

There are several alternatives whereby this increased power can be supplied to the furnace :—

(1) By increasing the current at the present voltage.
(2) By increasing the voltage.
(3) By increasing the number of phases.

(1) Power can be increased by increasing the currents at the present voltage values, and subdividing this current into two or more parallel paths through the furnace.

If the case of an 8,000-k.v.a. furnace at 85 volts to the bath be taken as an example, then over 47,000

amperes per phase for a two-phase, and over 31,000 amperes for a three-phase furnace will be required.

Since the largest electrode at present in use is the 12-inch diameter graphite, capable of dealing with 11,000 amperes, it would be necessary to use at least four electrodes per phase for a two-phase, and three per phase for a three-phase furnace, i.e. 8 or 9 electrodes for the furnace.

Transformers for dealing with such currents as above can be designed and manufactured, but only the furnace designers can give expert opinion on the possibility of providing for the numerous electrodes in the roof structure of the furnace.

(2) Power can be increased by raising the voltage between the electrode and the bath or, in other words, by increasing the intensity of the arc. The possibility of this suggestion is dependent on the roof lining of the furnace.

The author has seen the roof of many furnaces destroyed due to the destruction of the refractory material by the intense heat, so that to sustain a still further intensity of heat a stronger refractory material will have to be obtained or the roof protected in some artificial way. Here again is a problem for the furnace designer, as the transformers present no difficulties.

(3) The third alternative, that of increasing the number of phases, seems to be the one favoured by furnace designers as suggested in the papers on "Electric Furnaces," by Messrs. J. Bibby and V. Stobie, read before the Institution in May 1919.

Up to the present time, the author is under the impression that in this country the maximum number of phases used in a steel furnace has been three. Furnaces for four, six and eight phases have been designed and various transformer connections suggested and patented to obtain these requirements. None of these, however, has had, as far as the author is aware, any practical commercial trial up to the present.

The same difficulty presents itself here as in the first alternative, viz. a large number of electrodes is required.

There may be other advantages, such as a more equal distribution of energy and more economical production, and in the case of conducting-hearth furnaces the current may be kept within safe limits.

With regard to the special transformer connections referred to, it would be well to construct a small trial furnace before embarking on any large installation so as to avoid unworkable connections.

This suggestion of a trial furnace is necessary, for practical difficulties are not always apparent from theoretical considerations.

The practical limit of size for an electric furnace will, in the author's opinion, be a compromise between all three alternatives and will depend on—

(*a*) The maximum current that can possibly be carried per electrode.
(*b*) The maximum voltage that can be sustained across the arc without destroying the roof.
(*c*) The maximum number of electrodes that can be installed without danger to the roof.

Thus, if 11,000 amperes is the maximum current per electrode, the maximum voltage across the arc 90 volts, and the maximum number of electrodes 8, then the maximum size of furnace is 7,920 k.v.a. or approximately 40 tons.

The Design of Large Furnace Transformers.

The fundamental principles underlying the design of large furnace transformers are the same as those in power transformers, but, due to the large currents, special reactance and possible intricate connections, particular attention must be given to their design.

The reactance value required fixes the number of groups of coils, while the magnitude of the current determines the arrangement of the low-pressure parallel turns. The disposition of the parallel turns must be such that equal loading takes place, and, to attain this, conductors in parallel must be of equal length and have equal reactance.

In a straight transformer the designer's chief problem is the arrangement of the parallel low-pressure conductors.

This problem is more difficult of solution the larger the size of unit and the higher value of current to be catered for.

Since conductors above a certain width cause heavy losses, and above a certain breadth are difficult to obtain in long lengths, several conductors have to be used in parallel per coil.

As the size of unit becomes larger, the core section becomes greater, and consequently the low-pressure turns become few in number. This low number of low-pressure turns becomes more pronounced with shell-type than with core-type transformers; for, considering the same size of unit, the section of the shell is generally much larger than that of the core type for economical proportions of active material.

In connection with large shell-type transformers, the choice of the number of low-pressure turns often lies between one and two. If one turn is used, then a large iron section is necessary; or if two be used, a large weight of copper is required, while neither will give economic proportions of active material and minimum losses.

If $1\frac{1}{2}$ turns be used, as described in the author's patent No 131,026, a proportion of active material nearer to the economical value can be obtained (see Fig. 5).

If transformers with intricate connections are to be designed, as for instance with the low-pressure windings, Scott-connected, double Scott-connected, or Mr. J. Bibby's four or eight-phase connection, then further attention must be given to the arrangement of the low-pressure windings. With special connections such as the above, the currents passing through the coils on the same core are at different phase angles and so affect the reactance and possibly the terminal voltage, unless scientifically arranged.

The high-pressure windings do not in general require so much thought, for they can usually be arranged in series.

If tappings are required, their position should be such as not to affect the end-turn reinforcement, the disturbance of load in the low-pressure conductors to any great extent or, likewise, the reactance. This is affected usually by putting them in the centre of the winding

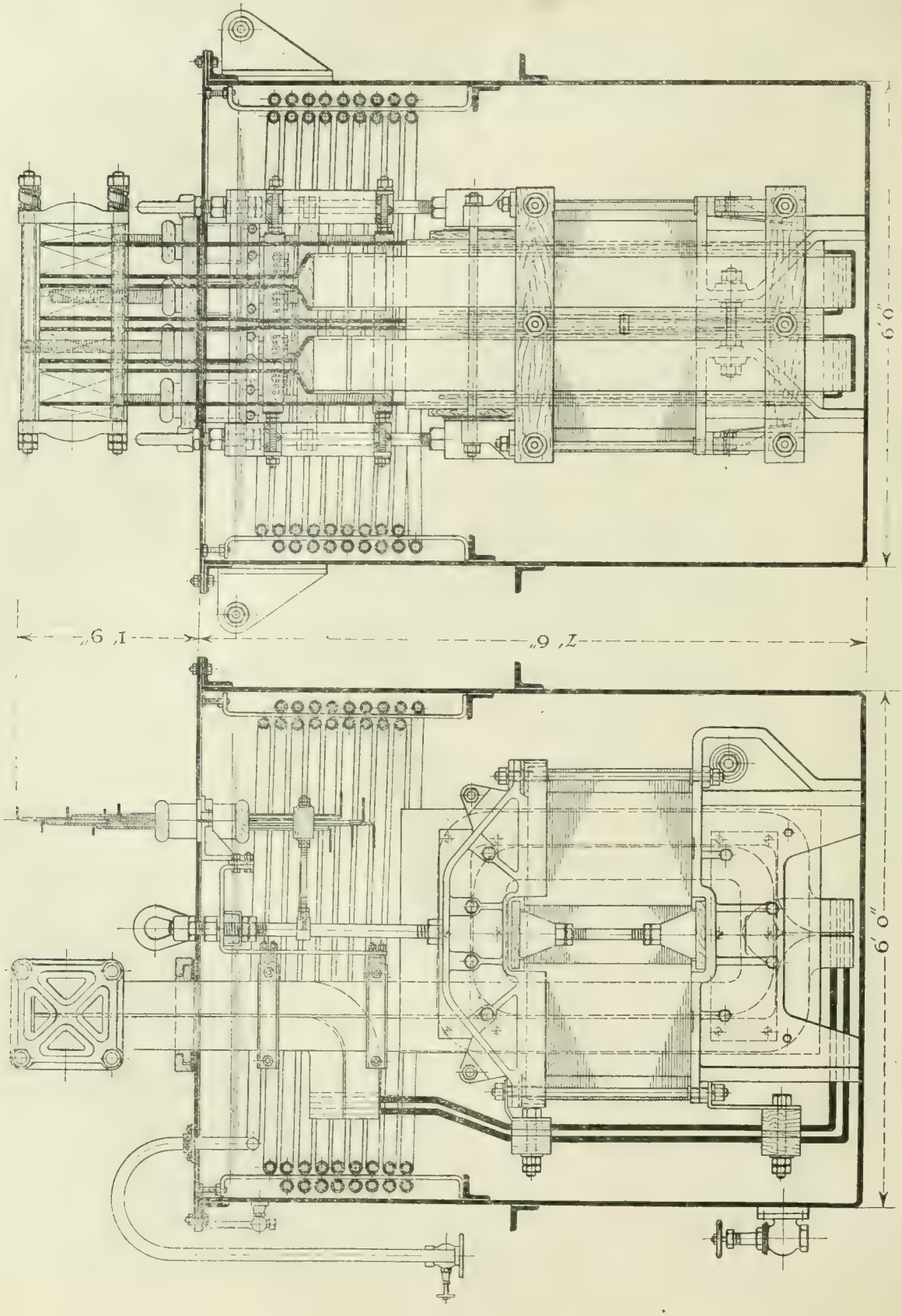

FIG. 5.—1,250-K.V.A. SINGLE-PHASE SHELL-TYPE FURNACE TRANSFORMER, ARRANGED WITH HALF-TURNS ON LOW-TENSION WINDING.

and also as far away from the low-pressure coils as possible.

The Ideal Furnace Transformer.

The ideal furnace transformer must fulfil the following requirements:—

Simplicity in design and operation.
Reliability.
Balanced loading under all service conditions.
Safety and continuity of supply.

In order to simplify the design and manufacture of furnace transformers, and especially those for heavy currents, it is desirable to increase the number of low-pressure coils in parallel. This increase in the number of coils in parallel consequently reduces the reactance value of the transformer.

A transformer of low reactance, while satisfactory for resistance furnaces, is unsafe for arc furnaces, hence the transformer reactance would have to be supplemented by an external reactance in either the high-pressure or low-pressure side.

An ideal transformer would also be one as simple as possible, having no tappings.

If voltage variation on the low-pressure side is re-

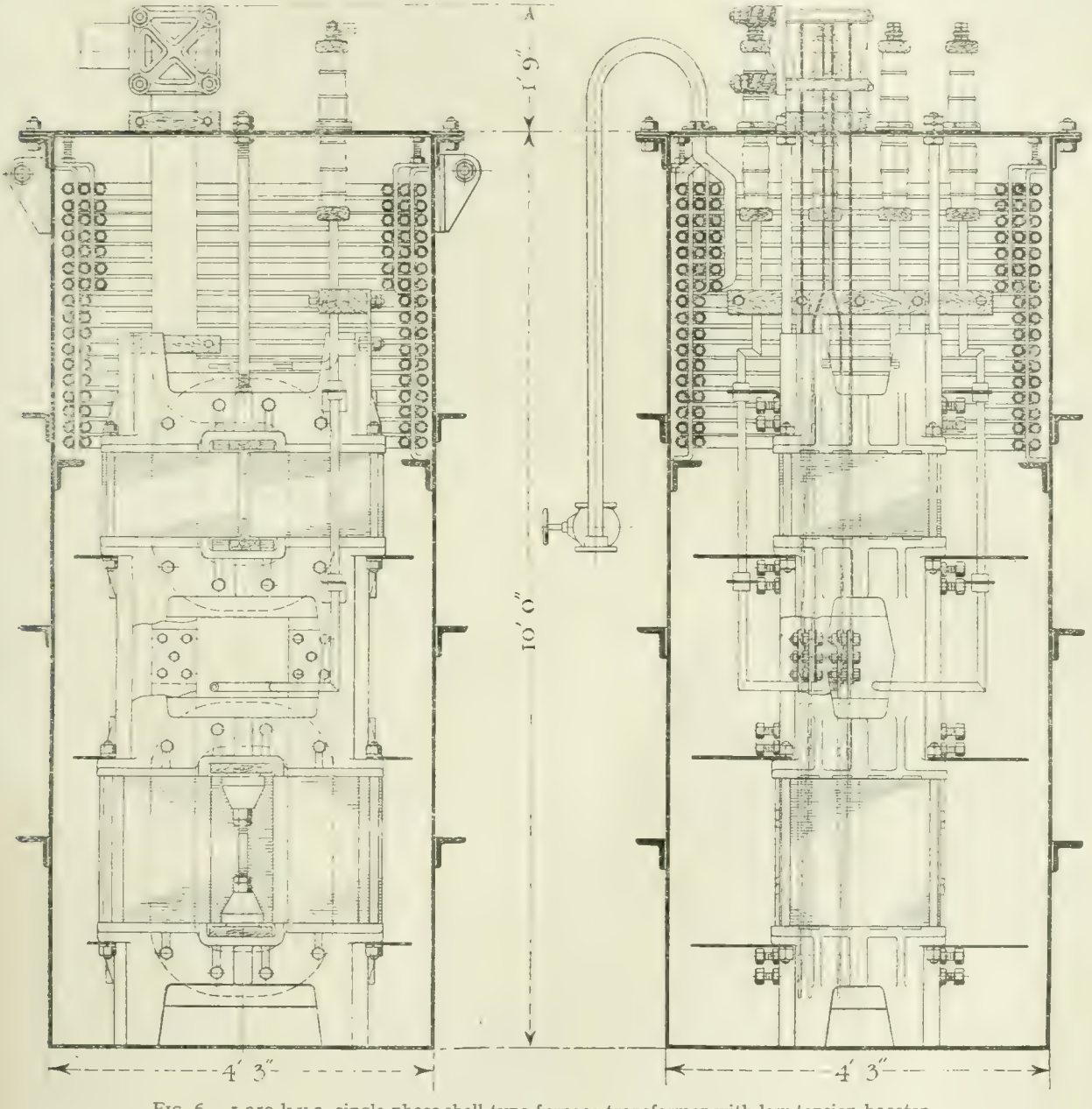

Fig. 6.—1,250-k.v.a. single-phase shell-type furnace transformer with low-tension booster.

quired, this would be obtained by means of a regulating transformer (Fig. 7), a booster (Figs. 6 and 8), or an induction regulator.

The regulating transformer may be an auto or double-wound transformer. If a booster is used, its primary winding can be arranged for the line voltage, and hence no tappings are required if only three voltage variations are necessary.

The three voltages can be obtained by using the booster positive or negative and by short-circuiting

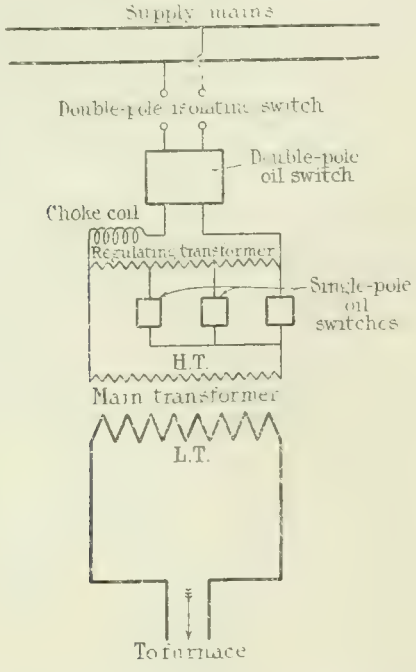

FIG. 7.—Diagram of connections of furnace transformer with high-tension auto-regulating transformer and external reactance.

the booster primary winding. The use of a regulating transformer, booster transformer, or induction regulator makes possible the same loading condition of the low-pressure coils at each voltage.

The regulating transformer can be wound for any voltage if double wound, so also can the booster transformer, but due to regulating switchgear the voltage is necessarily limited.

Induction regulators also have voltage limitations and also a low operating power factor.

Furnace transformers and the alternative auxiliaries above mentioned are suitable for all types of furnace, since the reactance being external can be varied at will or cut out.

If the external reactance be inserted in the line leads of the high-pressure side, it will also protect the transformer from voltage surges.

Since a large number of furnace transformer failures have been traceable to faulty insulation of tappings, the abandonment of tappings on the main transformer will increase its reliability.

In the suggested methods of voltage variation such as regulating transformers and boosters, tappings are sometimes unavoidable, but should these auxiliary units fail it is possible to cut them out and continue to run the furnace from the main transformer at some voltage. The voltage obtainable may not be exactly that for most economical production, but it will be serviceable and prevent a complete shut-down of the plant.

The ideal furnace transformer is, in the author's opinion, a simple transformer of one voltage ratio with a moderate reactance. The necessary auxiliaries for voltage requirements and safe working are an external

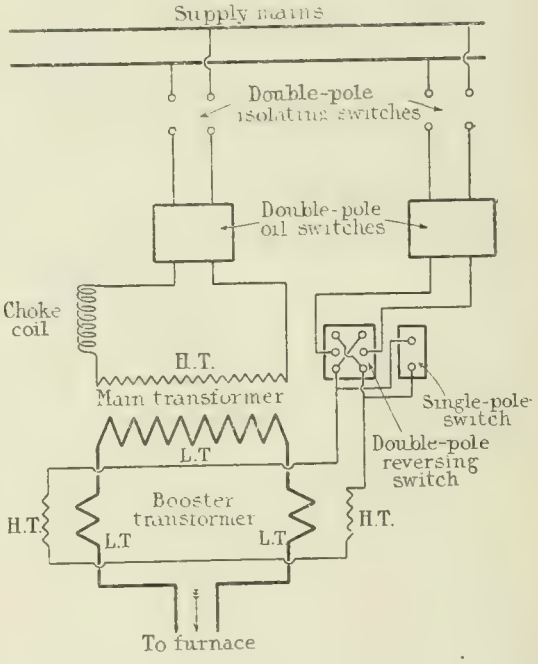

FIG. 8.—Diagram of connections of a furnace transformer with low-tension booster and external reactance.

reactance on the line side of the high-pressure winding, a regulating transformer, a booster transformer, or an induction regulator for voltage variation.

MECHANICAL STRESSES.

A great deal has been said on various occasions concerning the heavy stresses to which furnace transformers are subjected.

While this in a measure is true, it should not be interpreted to mean that the mechanical forces exerted on the transformers are of extremely high value, but that during operation frequent and repeated stresses of a moderate value are exerted. These stresses take place frequently during the melting period, and are brought to bear on the coils and leads.

The operating power factor during the melting period of a steel furnace (conduction type) is about 0·8. This figure is very difficult to obtain owing to unsteady load conditions, but from a study of many equipments and various tests and estimates, the power factor rarely exceeds the above figure until the bath is completely molten.

The type of furnace and the lay-out of the heavy-current leads controls the power factor to a certain extent, but 0·8 can be taken as an average figure. When the furnace bath is molten and the arcs become steady, the power factor rises to 0·9 or 0·92.

Taking the melting period with a power factor of 0·8, the reactance voltage in the circuit is consequently 60 per cent, so that if the arc should be short-circuited the maximum current would be 1·6 times full load.

When molten and at a power factor of 0·9, the reactance voltage in the circuit is 43·5 per cent, and permits of a maximum short-circuit current of 2·3 times normal. The mechanical stresses are dependent on the maximum currents that are allowed to flow through the windings; and to give an idea of the magnitude of these stresses a typical example will be taken.

A 2,000-k.v.a. 25-period single-phase shell-type transformer having a reactance of 7 per cent will, if short-circuited directly across its secondary leads, allow approximately 14·3 times its full-load current to flow provided the supply voltage is maintained This current brings a mechanical stress to bear on the coils in an axial direction of approximately 60 tons.

If the transformer is supplying a furnace and during the melting period (power factor 0·8) is short-circuited by the electrode coming into direct contact with the bath, the short-circuit current that will flow will be 1·6 times full load since the reactance in circuit is 60 per cent, i.e. 7 per cent in the transformer + 53 per cent in the furnace lay-out.

The mechanical stress due to this current is approximately 0·3 ton on the coils in an axial direction.

If the short-circuit occurs during the molten period, i.e. power factor=0·9, the short-circuit current is 2·3 times full load, for the reactance in circuit is now approximately 43·5 per cent, i.e. 7 per cent in the transformer and 36·5 per cent in the furnace and lay-out. This current brings a mechanical stress of approximately 0·8 ton on to the coils in an axial direction.

The figures of stress are those on the coil surface.

From the above example, it can be said that during normal operation furnace transformers are not subjected to heavy mechanical stresses by the short-circuiting of electrodes.

Heavy stresses are encountered, however, if the transformer low-pressure terminals are short-circuited, or if the primary windings between tappings become short-circuited due to failure of insulation or selector switchgear. While the stresses during normal operation are not heavy, they occur very frequently and, unless the coils and leads are clamped securely, failure of insulation may result after a period of service due to friction or movement of loose leads of different potential.

In the example quoted, the values of stress are those which occur when the short-circuit current reaches its final short-circuit value. These values may be quadrupled during the first cycle of a short-circuit according to the point of the voltage wave at which the short-circuit occurs.

Furnace Lay-out.

The satisfactory operation of electric furnaces is not dependent solely on the transformers being of correct design and sound construction, but also on the lay-out of the electric equipment. By lay-out is meant the relative positions of transformers and furnace and the heavy-current connections between them. The unscientific lay-out has been the sole cause in many instances of unsatisfactory operation.

The effects of a bad lay-out are chiefly—

Low operating power factors, hence inefficient working and a possible loss of useful working voltage.

Heating up of leads, clamps and cables.

Unbalancing of voltages on the furnace, and unbalanced load currents and phase relation on the supply side of the transformers.

The chief cause of lay-out trouble is that the inductance of the leads on the low-pressure side between the transformers and the furnace is either too high or unequal in the different phases.

This excess value or inequality of inductance causes heavy or unequal voltage drops in the leads.

The difficulty experienced in overcoming this cause of trouble grows with the increase of current, since the leakage field surrounding each lead or bunch of leads grows in proportion to the current.

In order to reduce the posssibility of a heavy choking effect and unbalanced voltages, the following suggestions will be helpful:—

(1) The transformer or transformers should be placed as near to the furnace as possible, so that the heavy low-pressure leads may be of minimum length.

(2) The low-pressure leads of the various phases should be symmetrically placed with respect to the transformers and furnace. This is essential so that the leads of each phase may be of approximately the same length, and also that the area enveloped in each phase should be equal, and hence the inductance of each phase equal.

(3) The area between the positive and negative low-pressure leads should be as small as possible, and also that between phases, in order that the inductance may be a minimum or of a practicable value.

(4) The low-pressure leads for heavy currents (above 5,000 amperes) should be in multiple and interleaved from the transformer to a point as near the furnace as possible. This will keep the inductance down to a low value and make that of each lead approximately the same, thus ensuring that each parallel lead takes its proper share of the load.

(5) The heavy-current leads should not be run near any heavy magnetic structure such as girders or supporting columns, unless both the positive and negative leads are run together and interleaved.

(6) No magnetic material should form a closed circuit around any positive or negative conductor, or heavy currents will be induced in that circuit. The positive and negative conductors interleaved may be run through a magnetic circuit. Clamps for heavy-current leads should be of non-magnetic material.

If the foregoing suggestions are followed, very little trouble will be experienced in connection with furnace lay-outs up to fairly large sizes. In the future development of electric furnaces much heavier currents will have to be dealt with than in the past. From the point of view of lay-out, it is possible that a maximum current limit will be reached for satisfactory operation. area results. The increased loop area, together with the heavy currents, brings about a heavy inductance drop and results in a low power factor, low electrode voltage, and inefficient working.

In some cases, as in the following example, very little additional energy is obtained on the furnace due to an increase in load.

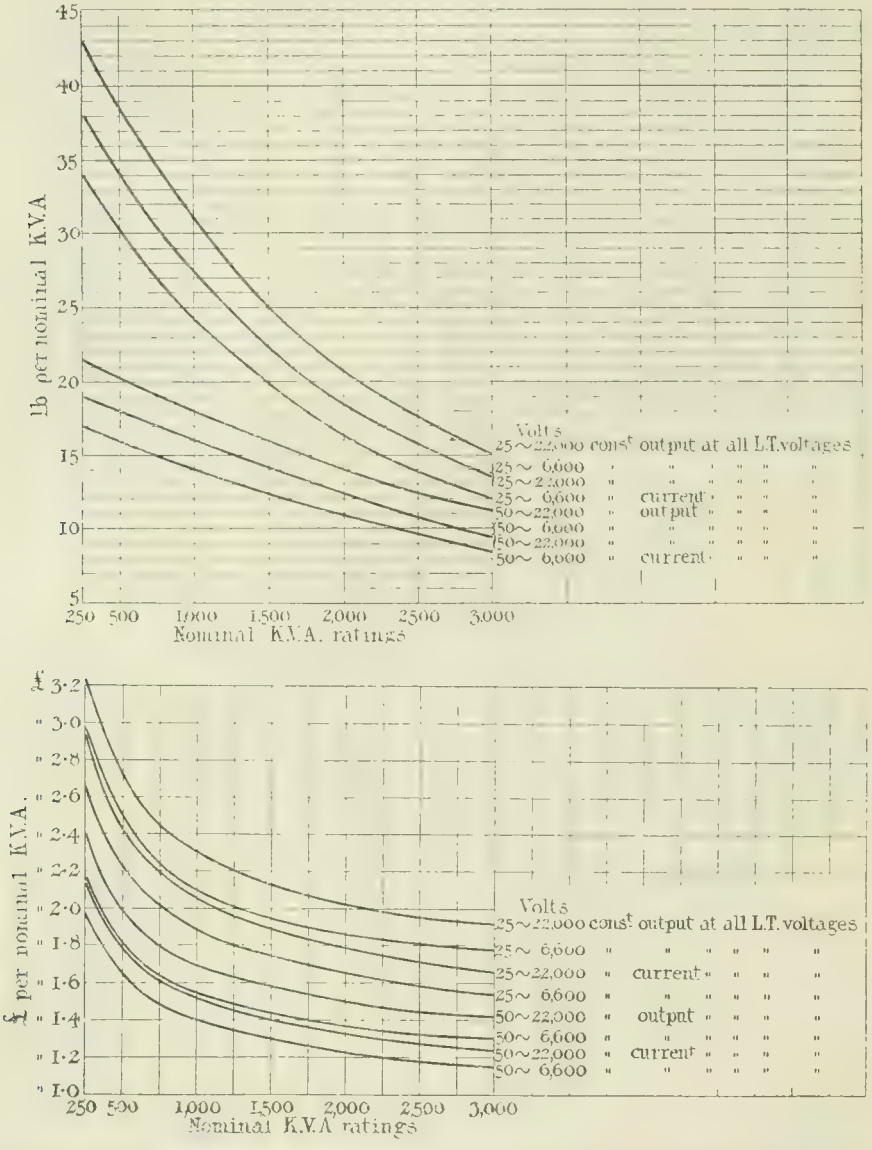

FIG. 9.—Curves of approximate weight and price per nominal k.v.a. rated output for single-phase oil-insulated self-cooled furnace transformers with low-pressure range of 1 to 1·31.

This limit is suggested by the fact that with heavier currents more latitude is required as regards loop area for the accommodation of the leads, and especially is this the case where they become flexible so as to allow movement of the electrode and the flexibles attached to them.

In the case of conducting hearth furnaces, the height of the loop becomes excessive and hence a large enclosed

As an example of the possible limitation of current, the following example will be of service.

Taking the 2,000-k.v.a. furnace transformer already referred to, this under the best working conditions has an operating power factor of 0·92. The lay-out of this furnace then has an inductive drop of approximately 39 per cent for a current of 23,500 amperes at a terminal voltage of 85. This inductive drop can be split up into

transformer inductive drop of 7 per cent and lay-out inductive drop of 32 per cent.

The above figures are those for an average case and represent a fairly good lay-out that cannot be much improved.

Now suppose the transformer, leads and furnace be replaced by one of 5,000 k.v.a., the transformer having the same reactance value of 7 per cent. Taking the lay-out to be similar to the 2,000 k.v.a. unit, but of heavier copper section, and the loop area the same, though in practice it would have to be larger, then the following would result:—

The load current is now 58,800 amperes with a terminal voltage of 85.

This will cause an inductive drop of $\frac{32 \times 58,800}{23,500} = 80$ per cent or a total of 87 per cent approximately, including the transformer. This results in the voltage across the furnace being only 49 per cent of the terminal voltage, i.e. 41·6 volts, and an operating power factor of 0·49. Thus although, for the same type of lay-out, the k.v.a. output has been increased from 2,000 to 5,000, i.e. 150 per cent, the power factor has dropped from 0·92 to 0·49, and the energy has only been increased from 1,840 to 2,450 kw. or 33 per cent.

Actual experiences similar to the above example are not uncommon, and point to a limitation of furnace size on account of limitations in lay-out. In other words, a lay-out suitable for a 2,000 k.v.a. unit is not suitable for a 5,000 k.v.a. unit.

The inefficient results given in the example above may be partially overcome by increasing the voltage on the low-pressure terminals, so that the resultant voltage across the furnace may be equal to that for the smaller unit.

For the 2,000 k.v.a. unit the terminal voltage is 85 and the furnace voltage 0·92 of 85, i.e 78·2 (neglecting resistance drop), while for the 5,000 k.v.a. unit the furnace voltage is only 0·49 of 85, or 41·6 volts.

Now suppose the terminal voltage of the 5,000 k.v.a. unit be 101 instead of 85, the load current would be then reduced to 49,500 amperes.

The inductive drop in the lay-out would be

$$\frac{32 \times 49,500}{23,500} \times \frac{85}{101} = 56{\cdot}6 \text{ per cent.}$$

The total inductive drop would be $7+56{\cdot}6=63{\cdot}6$ per cent, and so the operating power factor would be 0·77 and the voltage across the furnace $0{\cdot}77 \times 101 = 77{\cdot}8$ volts. As a result of increasing the terminal voltage, the increasing of the k.v.a. rating from 2,000 to 5,000 has increased the energy from 1,840 to 3,850 kw., i.e. 109 per cent, which is an improvement as against increased current only.

It will be noticed, however, that the power factor has fallen from 0·92 to 0·77, which is a low figure and points to the limitation of current capacity and lay-out already suggested.

Cost and Weight.

With reference to the cost and weight of furnace transformers, these are dependent on the maximum low-pressure current and the voltage variation required, apart from the variables of voltage and frequency.

In general, the furnace transformer k.v.a. rating is a figure much below that for a power transformer of the same weight.

For instance, take a 2,000-k.v.a. 25-period 6,000/65; 75; 85-volt transformer with full output at each

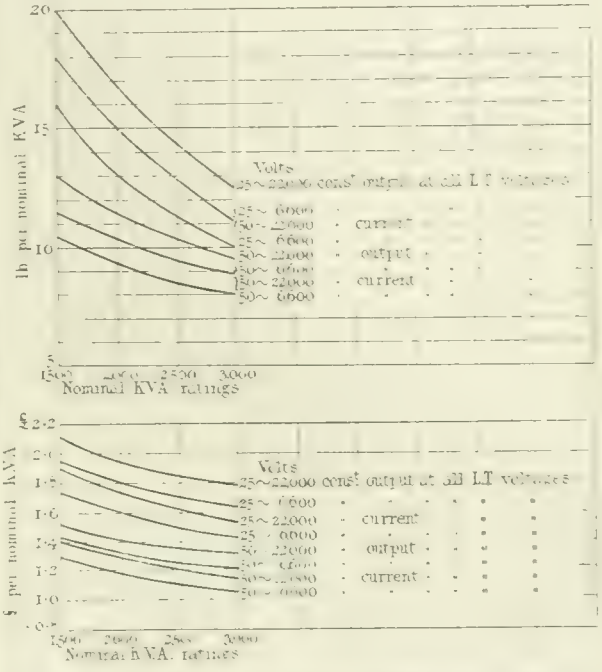

Fig. 10.—Curves of approximate weight and price per nominal k.v.a. rated output for single-phase oil-insulated water-cooled and oil-insulated force-cooled furnace transformers with low-pressure range of 1 to 1·31.

tapping; this would be equivalent in weight to a 2,620 k.v.a. power transformer.

If the low-pressure current is constant at each low-pressure voltage, then the equivalent power transformer for the same weight would be 2,310 k.v.a.

Approximate prices and weights are given in the curves, Figs. 9 and 10, for transformers whose voltage variation is obtained by means of tappings.

For furnace transformers complete with boosters or regulating transformers, the prices would have to be increased 10 to 15 per cent.

In conclusion the author wishes to express his thanks to The Metropolitan-Vickers Electrical Company for their assistance in the preparation of this paper.

Discussion before The Institution, 22 January, 1920.

Mr. H. M. Sayers: It is obvious that the design of a transformer for furnace purposes is, in a certain sense, a caricature of ordinary transformer design. The designer has to meet the conditions of a very abnormal ratio and of very heavy current in the low-tension winding, with the result that the design differs a good deal from that of a transformer for power and lighting purposes. The necessity for voltage regulation is another item which evidently causes the designer a good deal of perturbation, and the author has proposed, and has presumably tried, a number of methods for dealing with that. The liability to short-circuits in the furnace itself is a serious matter, much worse than a main fault on a low-tension distribution system, because there is no appreciable resistance between the transformer and the short-circuit. With regard to the loop reactance and the lay-out, it appears to me that the transformer designer ought to be the designer of the whole electric circuit from the transformer right up to the furnace electrodes and that he should either be able to specify, or know in advance, the loop area and the maximum reactance due to it, and make allowance for it in the voltage on the low-tension side. The only other kind of transformer which has anything like the ratio of turns and currents of the furnace transformer is the resistance welding transformer. There the ratio is even more exaggerated, and the "furnace" part as well as the transformer part is designed as one piece of apparatus. The electric furnace circuit and its transformer should also have the benefit of a combined design. With regard to voltage regulation, I gather from the paper that tappings on the primary are the most favoured. I also gather that the author is not very well satisfied with that condition of things, and I can quite understand that the supply authorities also are not very pleased with it. There may be cases where the method can be carried out without very much risk. If the transformer is fed from a star-connected three-phase system with the star-point earthed, then tappings at the neutral end of the primary would not entail a very great amount of risk, although I agree that additional primary leads to the transformer should be avoided if possible. The rational method surely is the one mentioned by the author, of using a booster external to the transformer and regulating on that. That has the important advantage of keeping up the power factor. There are one or two other points in the design which might be worth considering. The author apparently prefers to keep one flux path; and that one flux path means that he is confined to one or two turns, or to one and a fraction turns on the low-tension side. Surely that is a very awkward condition. Would it not be better to split up the flux paths and have a number of flux paths in parallel? I believe many advantages would follow from that, because the number of low-tension turns could be integral to start with. Every low-tension coil would be an exact replica of every other. All the connections, that is to say the lead lengths and the other dimensions, could be exactly similar. I rather think, though I have not worked it out, that the ratio of active to inactive copper on the low-tension side could also be made better if all the leads were of exactly the same length. There might be perhaps a little advantage in the insulation of the primary. If the primary is divided up into a number of coils on straight iron paths there will be less risk of breakdown to the core, without very much increase in the total amount of insulation. I shall probably be told that to split up the flux paths into a number of parallel paths would increase the amount of material. I think it would increase the amount of iron, and perhaps the amount of copper, but it would surely improve matters in other ways. It would make the disposition of the low-tension leads more manageable; it would also make it easier to support them adequately with regard to the forces that may come upon them in the case of a short-circuit, because those forces would be divided and distributed; and it would, I imagine, improve the cooling and the circulation of oil or other cooling medium through the transformer. Moreover, it would probably result in a somewhat larger external case, and that means that the whole transformer would work at a lower temperature. All those things seem to be worth considering. The old controversy of shell type versus core type comes up again in this paper, and the author shows a decided predilection for the shell type. From the point of view of the designer and the manufacturer that is understandable, and perhaps it is also affected by the question of competition and price; but from the point of view of the operating engineer I say most emphatically—and I have used transformers for a great many years—that the core transformer is much superior to the shell type, especially for the operating engineer who is far from a factory. Not so very long ago two fairly large core transformers with extra-high-tension primaries were delivered to me after a long voyage and an even longer wait in the custody of the Custom House, which were so saturated with moisture that they gave no measurable insulation on either winding. By careful treatment those transformers were dried out and then worked quite well, and I have not heard that they have given any trouble. Now I am quite sure if they had been shell transformers they would have been hopeless; nothing could have been done with them but to send them back to the manufacturers and to wait for 8 or 10 months for a new set or for the transformers to be repaired. Although that may be an extreme case, I have met with many other cases where the facility of inspection of coils and connections, and the facility with which repairs can be made, are very useful features of core transformers. In the shell transformers, beyond the few inches or foot or two of leads which are visible, one cannot see anything about the coils, and if anybody has ever tried to take to pieces a shell transformer without a transformer hand helping him he must have been amazed at the result and despair of ever putting the transformer together again. The probability that very much larger furnace

transformers will be required in the near future renders this paper of great importance. There are countries which, having very large amounts of iron ore and no coal, and also having very large water-power, will reduce their iron ore to iron by means of electric furnaces, and they will not want 6,000 or 7,000 kw. transformers for such work ; they will require 60,000 or 70,000 kw. per range of furnaces—I do not say in one transformer —and that is going to be a very important matter.

Major A. M. Taylor : From one or two previous papers on this subject a sort of hazy idea was conveyed that there was a large amount of reactance in the secondary circuit. I thought that perhaps it was in the furnace itself, but apparently it is principally, if not almost entirely, in the connections. The results of the author's observations appear to be that really there is so much reactance in the leads—design them how one will—that a very severe short-circuit is impossible. That is rather interesting in view of the description, put forward about nine months ago, of the Westinghouse furnace transformers, in which the impression was given that there would be very severe stresses on the windings. I do not offer any comment, except that the author's figures seem to justify his statement that there is no very severe stress. There is one thing in Fig. 8 in which I am rather interested, viz. the booster. I do not know whether it has occurred to the author that if the high-tension winding of the booster could be twisted round through 120 degrees on to the next phase of the supply, he would then get a boost in the secondary circuit of the main transformer in such a sense as to bring the power factor up to unity on the main supply, at the expense, however, of the current in the high-tension winding of the booster. Suppose the high-tension winding of the boosters were put on to a special feeder which ran back to the power station, and the whole were supplied from a separate generator intended to give merely the wattless components ; the main supply would then operate, as far as the furnaces were concerned, at unity power factor, and would get all the benefits due to that condition. Incidentally in that connection I would mention that during the last six months I have found it possible experimentally to superpose two systems, a 25-period system and a 50-period system, and yet to have the two systems absolutely distinct, so that the frequency and voltage of either system can be varied at will without interfering with the other. That could be applied to existing systems, and one could connect with advantage all the furnace transformers to this superposed system, which utilizes the existing mains without alteration. One would thereby avoid the fluctuations in the supply to lighting and other consumers, and transfer such fluctuations to special generators running on separate busbars, which might perhaps be interlinked with reactances on the main busbars. That seems to me a possible scope for improvement. I hope some day to describe the experiment which I have made of passing currents of different frequencies over the same system. There is a question in that connection which I should like to ask. Perhaps the author can state whether most furnaces are equally suitable for working at lower frequencies, or whether they must all be worked at 50 periods in order to get the best results. Many towns have only a 25-period supply, and it would be interesting to know whether furnaces can be equally well worked at 25 periods as at 50. If they cannot, perhaps what I have been mentioning might be a way out of the difficulty. The author alludes to the Scott-connected transformers in words that makes me think he does not quite like this connection.

Mr. S. E. Fedden : The high-tension tappings which the author brings out from these furnace transformers have in Sheffield always been a cause of failure, more especially on the Scott-connected transformers, and if such tappings are essential I think each one of them ought to come to a separate terminal, because in almost every instance they have broken down and flashed over. On page 206 the author mentions a furnace of 15 to 30 tons' capacity supplied from a 8,000-k.v.a. transformer. This furnace will have to be of an oblong or oval shape with long sides, instead of a round furnace. From my experience in Sheffield I should very much prefer to feed it with four sets of 2,000-k.v.a. transformers—if possible having a set of transformers to each pair of electrodes—than to put all the transformers into one group, say of 8,000 k.v.a., because if the transformer sets can be divided up and placed as close as possible to the electrodes the self-induction of the leads will be reduced, a very much better power factor will result, the losses will be reduced, and the lay-out will be much cheaper, although the transformers may be slightly dearer. The author mentions the necessity of care in the lay-out. In the early days in Sheffield when we put in either our first or second furnace, after it was connected up and the motor-generator was running and giving full power, we found we had practically no power on the electrodes at all, although the ammeter showed full load. Then somebody happened to lean against a stanchion near the leads and found that it was very hot. All the power was going into this steel stanchion instead of into the electrodes. That only confirms what the author says about having to be careful of the lay-out. On page 207 the author speaks about the intricate connections with double Scott-connected transformers. I think that Scott-connected transformers are really unnatural. We have to use Scott-connected transformers, but I cannot say that I am nearly as satisfied with them as with an ordinary three-phase set or single-phase sets. On page 210 the author suggests the use of boosters, which I think is a very much better arrangement than to bring out tappings. With regard to the stresses, on short-circuiting a furnace with no reactance, we had a case of a furnace not far from the power station where the electrodes were lowered before the main switch was closed, so that there was a dead short-circuit. The total load on the station was about 59,000 kw. at the time. The result was that the man in charge of the furnace was blown through the door, the main switch burst, and the service mains were volatilized. This shows what stresses there are to contend with on furnace transformers. With regard to regulation, if there are a large number of machines running one does not mind the variations very much. We have had, during the war, variations of 6,000 kw. off and on many

times a minute. When only one machine is running it is absolutely necessary to use a regulator, but with three or four machines running I find that I can remove the regulator altogether and the machines will look after the load exceedingly well, so that one will only see a flicker in the lights even with these tremendous variations in load. At the bottom of page 210 the author says : " If the external reactance be inserted in the line leads of the high-pressure side, it will also protect the transformer from voltage surges." We have found in practice that the reactance we installed —which is merely a lot of stampings round the low-pressure leads with an air-gap—is quite effective.

Mr. R. G. Mercer : It seems to me that the author has based his conclusions regarding recent transformers from those which were supplied to electric furnaces some time ago, and from the experience of troubles on those furnace transformers. In my opinion those troubles were due to various causes. They were partly due in the early days of transformer design to the makers themselves not being sufficiently acquainted with the heavy surges from electric furnaces, especially during the melting-down stage ; and they were partly due to the makers of the furnaces in very many cases installing transformers of too small a k.v.a. capacity. In two or three cases to my knowledge transformers of too small a k.v.a. capacity were installed mainly on the guarantees given by the transformer makers with regard to the heavy overload capacities which they stated could be obtained with their transformers—20 per cent for 24 hours, or something like that. Thus the furnace maker would take, say, a 600-k.v.a. transformer for a 3-ton furnace, add 20 per cent, and call it 720 k.v.a., without regard to temperature rise. In those days it was never brought home sufficiently that there was a third contributory element to the failure of these transformers, namely, the users of the furnaces and the melters of steel themselves. The author may possibly be aware of several cases where transformers broke down due entirely to negligence on the user's part. For instance, there was stripping of the raising and lowering gear, with the result that the electrodes came right down to the hearth, and in the case of a furnace with a bottom connection there would be a dead short-circuit, the resistance of the hot hearth bottom being negligible. The transformer maker in many cases was called upon by the user to put the transformer right, and was severely censured for supplying a transformer which would not stand up to furnace conditions. Those troubles are yesterday's troubles, and to-day there are new conditions, and I here wish briefly to draw the author's attention to the fact that I do not think he mentions in his paper some of the conditions whereby the transformers of to-day can safely be assumed to be more reliable than those of yesterday. There are first of all transformers of a higher k.v.a. capacity ; for instance 800 k.v.a. would now be installed instead of, say, 650 k.v.a. for a 3-ton furnace. There are automatic voltage and current regulators which will take care of the scrap from the cold to the molten stage. In the works with which I am now associated we have one of the biggest electric furnaces in the country, a 15-ton furnace, which has behind it 3,000 k.v.a. A year ago a similar sized furnace had 1,500 k.v.a. behind it, and the transformers broke down in course of time. To-day that same furnace has now 3,000 k.v.a. behind it, and it has a maximum of somewhere about 2,800 k.v.a. to stand up to. It has no very heavy surges, because it is fitted with automatic voltage and current regulators, which take care of it from the breaking down stages (which are the most severe, where one gets all the surging) to the molten bath. In the furnaces of anything above 4 or 5 tons' capacity I think one will find that automatic voltage and current regulators will in future be employed. With furnaces of about $3\frac{1}{2}$ tons' size the general practice is to have hand electric control, and in small half-ton furnaces direct hand control, and it may not be worth while to go to the expense of installing automatic regulators for those small furnaces. Another cause of the trouble in electric furnaces, transformers, and general lay-out, is the habit that users have where the furnace is designed to take, say, 4,000 amperes per phase, to run it at, say, 6,000 amperes per phase. This consequently increases the current density not only of the low-tension conductors but also of the electrodes, and here I may mention that it was the practice in a very large number of cases to install low-tension conductors with a current density of 1,500 amperes per square inch, whereas to-day's practice would bring this down to from 700 to 900 amperes per square inch. Amorphous carbon electrodes were run at as high as 40 to 50 amperes per square inch instead of present-day practice, namely, 25 amperes per square inch. Graphite electrodes were run at 150 amperes instead of 100 amperes per square inch. If we add to these high current densities the increased input as stated above, it can readily be imagined that not only do the electrodes heat up considerably, but also the low-tension conductors. This has in one special case in my mind resulted in a heat drain back to the transformer which was already overloaded and overheated. There have also been cases where the switchgear has refused to trip, due to accumulation of grit and general neglect, and the transformer was consequently called upon to take excessive overloads. The author talks about increasing the low-tension voltage, but I think there is a limit to this, because by increasing the voltage on the low-tension side we pull a longer arc, with the result that instead of muffling the arc in the slag it is more exposed and the refractories would suffer in consequence. There is furthermore, in my opinion, a limit to the rate at which steel should be melted. There is no doubt to my mind that a higher low-tension voltage than that at present employed could be used if we could obtain a carbonaceous atmosphere under the furnace roof, thereby protecting it. This brings one to the question of having a satisfactory seal, or what is known as an electrode economizer, to stop gases coming out through the electrode entrance in the roof. This is very difficult to obtain with the " gallows arm " type of furnace, but too much importance cannot be attached to it. This question was very fully dealt with in a paper read before the Institution last spring,* and one can readily conclude that with a satisfactory economizer the user not only obtains his steel at a lower

* R. G. Mercer : " Electric Furnaces in the United Kingdom, 1918."

current consumption, but gets a greater output in view of the shorter heat period.

Professor S. P. Smith: I should like to ask the author one or two questions in regard to the reactance to which he repeatedly refers. Why is the internal reactance in the transformer required? Is it in order to safeguard the transformer? It would appear from the paper to be necessary to have a certain minimum reactance depending, I take it, upon the type of the load. With regard to the total reactance of the secondary circuit, we are told that 32 per cent in the leads represents perhaps about as good conditions as we can get. In addition we have 7 per cent in the transformer, making altogether 39 per cent. Of course that 7 per cent is not very important in the total, and I should be glad if the author would give a little more information regarding the necessity of this internal reactance. There are many reasons why one can prefer the core type to the shell type, though the usual reasons have been already given. Thus the teacher prefers the core type to the shell type because it is very much easier to demonstrate its construction to the students; while the designer finds it very much easier to design the core type than the shell type. When the author showed me how to design transformers, I well remember that in the case of a shell-type transformer it was rather a difficult matter to fit in the coils and the insulation. I should also like to ask the author if it would be possible to design a core-type transformer for furnace work having only one or two turns. Further, if one could use the core type, could the coils be made concentric, and the reactance obtained in the same way as in the case of a high-reactance transformer for a rotary converter? Lastly, I should like to ask whether with a booster, which seems to be the ideal arrangement, the author would make the transformer highly reactive, or would he use a transformer with normal reactance and obtain any further reactance required either in the booster or in the leads?

Mr. J. R. Cowie: I want briefly to refer to the core-type transformer. It has been mentioned by two speakers. The only advantage I can see in it is the ease of repairs, as mentioned by Mr. Sayers. I think the author would make his point clear, and help young members, if he would give us the stress figures for the core-type transformer of a similar size to the figures given on page 211. I have taken those figures on page 211 as being for a shell-type transformer. If he would also give us the efficiencies for the core-type transformer and the shell-type transformer he would make his point clear. I expect to find the core-type transformer fail badly in efficiency. That is indicated by the author. On page 206 attention is drawn to the leads. I have seen a big power transformer sent out from the manufacturer's works where the leads crossed all right. Not only did they cross, but they touched—an absolutely dangerous job—and I am glad the author has drawn attention to that point. With regard to limitation of furnace size, I think we have got to face the big transformer. I have had one or two propositions put up to me for fairly large transformers surrounded with smaller transformers to do the refining work, and that raises an awkward question from the supply authority's point of view, namely, to get the power to the job. I had some figures taken out of the cost of an 11,000-volt cable, and it works out at £3 12s. per yard. If we take a 22,000-volt cable that works out at £4 per yard, including all street reinstatement. The power ratios of the two cables are from 1 for the low-voltage to between 1·75 and 2 at the higher voltage; and look at the difference of capital cost in the cable. This means, if the smelting people wish for the lowest possible price, that the best possible conditions (that is, the least capital expenditure) from all parties' points of view, must be obtained for each individual case. The cost of switchgear ranges from 1 to $2\frac{1}{2}$ if a light 22,000-volt gear is used, and from 1 to 4 if a very heavy high-tension switchgear is used. The switchgear cost is generally a very small proportion of the total. On page 210, regulators are mentioned. Like previous speakers, I do not like any more than the author does tappings coming out from the transformer, and modern progress is certain to go along the lines of regulators. There is a regulator which has not been mentioned, which is in operation now and which gives ranges of 95 to 190 volts, and on another tapping of 25 to 95 volts. That is a high-tension regulator. The same regulator can be designed to give 20 per cent regulation with not more than 600 volts on the regulator. When I turn to the curves on page 212, I notice how the weight drops as the size increases, and I notice that the price curve does not fall at the same rate. That is understandable. It seems to me to come flat owing to the greater difficulty of making a mechanical job of the big transformer. The figures given on page 213, I think, include the capital cost of the water-cooling outfit or the oil-cooling outfit, but that point is not clear. Another point the author has mentioned is the question of using $1\frac{1}{2}$ turns. I have been told lately that a transformer with an odd number of turns has been on the market for a number of years.

Mr. G. E. Taylor: There seems to be great doubt about the tappings on the transformers. We have something like 50,000 k.v.a. in steel furnaces in this country, and about 100,000 k.v.a. altogether in other furnaces. We always use two or three tappings. We have had one or two burnt out, of course, but we have never had in any one instance the tappings go in any shape or form. The fault has never been at the tapping point on the transformer. As regards the reactance in the transformers, undoubtedly a certain amount of reactance is required in transformers for steel furnace work, and in a large furnace of about 6 or 7 tons one will get something like 30 per cent reactance in the leads. It does not matter how it is designed, one cannot get much less than 30 per cent reactance with a line voltage of 90. The author also mentions the use of a much thicker lead on the transformer where it comes out of the oil to the low-tension terminals. There is no doubt this is required, as the old transformers warmed up at this point. In the first furnace transformer that we had, the reactance in the transformers was provided by iron shunts. That reactance is of little use in the furnace. One must have a reactance that obeys a linear law. About the same percentage reactance is used in furnaces now-

adays, but the short-circuit current does not rise to the same amount as it did in the old transformers. On the Teeside we have a furnace the power factor of which over a period of six months averaged 0·9 to 0·92. The author mentions a power factor of about 0·8 on melting. I have taken several power factors, and it certainly comes down to about 0·8 momentarily, but it is so unsteady that one cannot read the meter very well. If 0·9 to 0·92 be taken over a period of six months, considering that the melting period is much longer than the refining, one cannot see how 0·8 is an average over the melting periods.

Mr. H. W. Clothier: The author in his ideal transformer puts "Safety" as one of the headings, and has referred to the dangers due to failure of insulation on the transformer terminals. It seems to me that in all designs of this kind we should set out with the fundamental idea of enclosing all the high-tension conductors, and I suggest that this should receive more attention from transformer designers.

Mr. H. S. Holbrook (*communicated*): All transformer builders will, I am sure, agree with the author that the ideal transformer is one of moderate reactance with only one voltage ratio. Perhaps more transformer troubles, both in the design office and on site, have been traced to the tappings than to anything else, and it is usually a much better engineering proposition to use auxiliary apparatus for voltage variation, although the first cost may be greater. Again, reactance for current-limiting purposes is best obtained by apparatus specifically designed for that purpose, such as that shown in Fig. 26 on page 289 in Mr. Wedmore's paper in volume 56 of the *Journal*. The author has given some figures indicating the floor space necessary in transformer substations, but what size of ventilating apertures, in the walls or in the floor and ceiling, would he recommend for a substation containing, say, one 1,250-k.v.a. transformer like Fig. 1 or Fig. 2, assuming that the inlet air duct did not exceed 5 feet in length and the outlet duct say 10 feet, with the inlet air at the ambient temperature of 40° C.? When a furnace is installed in an existing building, the transformer is sometimes almost totally enclosed. It is certainly not well-ventilated. What is the efficiency of the transformers shown in Fig. 1 and Fig. 2? The author recommends interleaved low-tension leads for currents higher than 5,000 amperes. I should like to ask what cross-section (size and shape) at 50 periods he recommends for this current. Would it not frequently pay to interleave conductors carrying smaller currents than this, in view of the greater current density then permissible and the greater surface exposed for cooling? After reading the author's comparison of core and shell-type transformers, one gets the impression that he favours the shell type. It was the same in the recent paper he presented in conjunction with Mr. A. G. Ellis.* The discussion on that paper revealed the contradictory views held on this question, and the only conclusion appears to be that given by the author himself in the previous paper: "... the types recommended by individual manufacturers depend largely on their experience and manufacturing facilities." The author states that the stray loss in the core-type transformer is much greater than that in the shell type. Can he give us the percentage values of this loss for the transformers in Fig. 1 and Fig. 2? If we consider the question often confused with this one, viz. the relative merits of circular and rectangular coils, then only one conclusion is possible, and it is rather surprising that the author did not mention it when considering "mechanical stresses." Circular coils are best. The accompanying diagram (Fig. A) will, I think, show this better than a description.

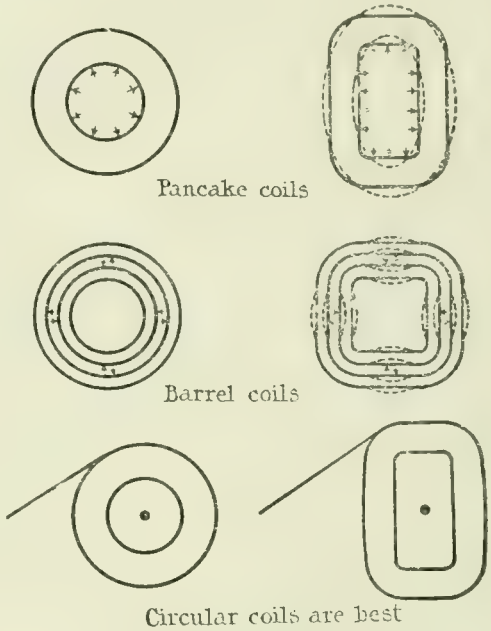

FIG. A.—Circular and rectangular coils carrying large currents.

NOTE.—All coils carrying current tend to take the form which will include the maximum flux. The resulting mechanical forces are perpendicular to the conductors. In circular coils the forces are radial and there is no tendency to distortion. In rectangular coils the forces tend to bend the conductors and cause the coils to change their shape as indicated by the dotted lines. Rectangular coils are inherently weaker to withstand this stress, as, due to the varying distance during winding from the former spindle to the conductor, it is practically impossible to obtain a uniform pressure across the coil, as shown on any rectangular coil by its varying width.

Mr. H. H. Ashdown (*communicated*): It may be of interest to mention that Messrs. Sir W. G. Armstrong, Whitworth & Co. have had in operation for some time past at their Openshaw works a 12-ton Stobie electric furnace. The author shows on page 206 a very optimistic spirit in looking forward to electric furnaces of 30 to 40 tons' capacity; I fear that as regards this country they are in the distant future, unless a very cheap source of power becomes available. The author's suggestion on page 207 of putting down a trial furnace

* "Large Power Transformers," *Journal I.E.E.*, 1919, vol. 57, p. 547.

of large capacity for elucidating practical difficulties is excellent, but the main difficulty is to find financial people who are prepared to take the risks of failure. If, as the author points out, furnaces of this type do develop it will be necessary, owing to the large number of electrodes required, to devise means for supporting the greatly weakened roof.

Mr. V. Stobie (*communicated*): This paper deals with a section of electric furnace plant which has hitherto not received very considerable study by many of those engaged in designing, installing and working electric furnaces; and it is to be hoped that other transformer experts will offer their experience to help the electric steel industry to attain still more quickly the high efficiency which alone will breach the now small gap between the cost of electric steel manufacture and other steel melting processes. Fig. 2, showing a 1,250-k.v.a. shell-type transformer, does not carry out the author's statement that only the high-pressure leads required should be brought out of the case. I support his statement and disagree with his drawing. I have seen cases where the high-tension current has leaped across outside terminals such as those shown in Fig. 2, even when the terminals have been 6 or 8 inches apart. This has not only taken place when a high-tension winding has failed under load, but even when there has been no defect in the transformer. I have observed this only on overloaded transformers, and think the reason may be that an atmosphere of hot oil vapour rising from the tank has been sufficiently conductive to enable the voltage (possibly locally augmented at the moment) to bridge the terminals. The subject of the interleaving of the low-tension conductors from the transformers to the furnace is one on which opinions differ considerably. It is true that interleaving will keep down inductance and (according to the scheme of connections) sometimes the skin effect in the multiple conductor; but the extra cost of labour and material necessary for interleaving the heavy conductors, plus the greatly augmented number of contact joints this entails in the leads, make the gain too remote. As the author has stated in another part of the paper, it is necessary to have reactance in an electric furnace installation, and undoubtedly the best place to get it is in those parts of the installation where cost varies inversely with reactance. The following data on two Stobie furnaces each of about 15 tons' capacity may be of interest in regard to reactance:—

Normal current per electrode	7,500 amperes
Average length of phase circuit ..	100 ft.
Reactance in transformers	15 per cent
Power factor when melting	0·84
,, ,, melted	0·93

There is no interleaving whatever in the circuits, yet with 15 per cent transformer reactance the above excellent power factors are obtained. I have recently heard of an arc-resistance furnace installation which, although its multiple conductors are interleaved, gives a power factor below 0·5. The crux of the matter is in the juxtaposition of the whole of the installation rather than the run of the separate conductors. Many good points are advocated in the section of the paper dealing with the ideal transformer. I have already in operation at my own steelworks the combination of a regulating transformer with a main transformer which the author suggests as part of the ideal scheme for avoiding tappings on the high-tension side of transformers. It has the disadvantage of providing a second possible source of breakdown. If the regulating transformer broke down it could, as the author points out, be cut out; but as only the highest low-tension voltage would then be available for working the furnace, the latter would be unmanageable unless it were engaged solely on steel for castings, which steel alone would admit of such a high voltage for finishing. Other disadvantages are the extra cost of apparatus and the constant losses in the auxiliary transformer. I have no experience of the booster arrangement mentioned in the paper. If the auxiliary booster windings broke down, the whole transformer would be shut down unless it were decided never again to use the boostering portion of the plant. My preference will always be for an efficiently safeguarded arrangement of tappings on the high-tension side of furnace transformers, unless some totally new method of altering the low-tension voltage is devised which does not increase the possible sources of breakdowns. The data given on page 211 relating to the axial mechanical stresses on the coils due to overloads are very interesting. It is conceivable that, as the author points out, these stresses have been overrated hitherto. Again speaking of my own experience, I consider radial stresses in a transformer to be more important from a designing point of view than axial stresses. The windings abut axially on very stiff insulating supports; but radially there is no serious mechanical backing offered the coils. The result is that one has to rely almost solely on the tensile strength of the copper wire resisting rupture by the radial stresses. This it by no means always succeeds in doing and, unfortunately, one cannot rely on axial pressure on the windings helping to resist, by friction, the radial stresses. If the author could devise, with certainty, a means of rididly supporting the coils against radial stresses, he would doubtless solve three-quarters of the high-tension troubles in furnace transformers. His considerable experience in designing furnace transformers makes me very hopeful of his being ultimately successful. On the subject of future requirements the author makes several interesting remarks. Furnaces of 30 and 40 tons' capacity will doubtless be much used in the future. A 30-ton Stobie furnace was decided upon for one British steelworks in 1918, but the Armistice cancelled the necessity at the time. The process decided upon was to melt scrap continuously in the 30-ton furnace and run 12 to 15 tons of the oxidized and dephosphorized bath into a second electric furnace for finishing. This process, the details of which are patented, affects the transformer installation in several ways. The short-circuits are reduced to less than one-tenth the frequency and half the magnitude of those experienced in the ordinary electric steel process. The transformers have a load factor of upwards of 95 per cent as against the usual 70 per cent. The power factor of the installation averages 0·9 as all arcs are either steady or nearly so, and the lay-out follows my normal practice. The foregoing would tend either to

cheapen the transforming plant or to provide a safer limit of working for the transformers. Of the alternatives given on page 206 for delivering greater energy for larger furnaces, No. (2) is incorporated in Figs. 2 and 3 in my paper on "Large Electric Steel Furnaces" read at the Joint Meeting of the Institution and the Iron and Steel Institute last May. By putting two electrodes in series on each phase, the voltage per phase can be nearly doubled. Instead of having four-, six- and eight-phase transformers in large furnaces, I would prefer two two-phase, two three-phase and four two-phase with two electrodes in series on each phase. Such arrangements simplify and facilitate the connections and offer every possibility that the other methods do.

Mr. J. L. Thompson (*in reply*): The remarks of Mr. Sayers upon the abnormal requirements of transformers for furnace work coincide with the author's statements in the paper, and clearly show the difficulties with which the designer is confronted when designing this type of apparatus. The lack of information with

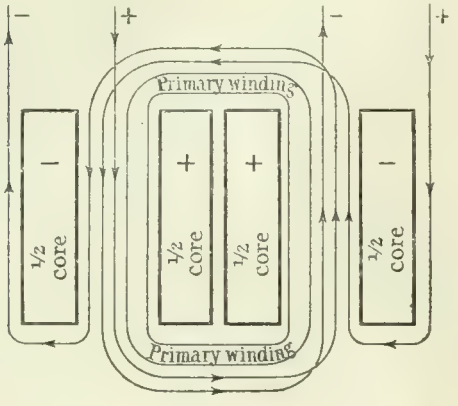

FIG. B.—Diagram of $1\frac{1}{2}$ turn winding.

regard to operating conditions in the past, and the abnormal specifications of furnace makers, have retarded development considerably and, at the same time, have thrown an unjustifiable burden on the manufacturer of furnace transformers. Voltage regulation is an essential, and although the use of tappings is the method commonly adopted it is far from perfect. No doubt the question of cost has given this method a longer life than it would have had, had reliability and safety been fully considered. The author disagrees that short-circuits in a furnace are worse than a main fault on a low-tension distribution system, unless that fault be a long way from the source of power. The author has tried to prove this on page 211 under the heading "Mechanical Stresses." The author agrees with Mr. Sayers that the lay-out should be treated as part of the transformer designer's problem, but due to the conservatism or fear of appropriation of so-called patent lay-outs and connections, the transformer engineer has not yet been allowed this privilege. Many cases have occurred, chiefly with larger types of furnaces, where the original lay-out had to be modified in consultation with the transformer engineer before satisfactory operation could be obtained. The author has experienced several cases of original lay-outs designed by furnace makers or consulting engineers, which gave operating power factors of 0·5 or 0·6, and which when redesigned gave satisfactory operation at power factors of 0·85 and 0·9. Mr. Sayers suggests that regulating tappings should be at the neutral point. This is, of course, possible on a three-phase furnace star-connected, but if so placed voltage surges may pile up at the dead end of the winding, or the voltage across the winding may become high when working on the highest low-tension pressure. If the tappings were in separate sections that possibility would be overcome. All furnace transformers are not star-connected, some being delta and others Scott-connected, and in these the neutral point is not available; hence the best position for tappings is in the middle of the winding. Mr Sayers's suggestion of flux paths in parallel for overcoming the half-turn problem is exactly the method used in the author's Patent

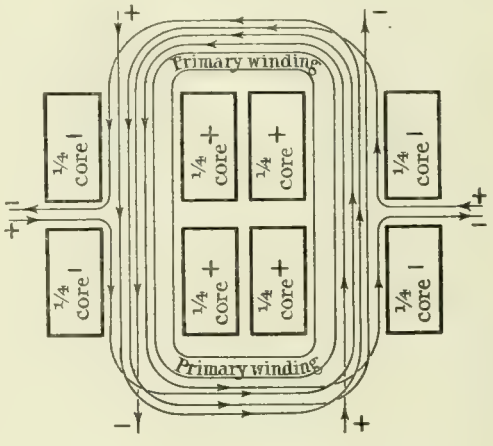

FIG. C.—Diagram of $1\frac{1}{4}$ turn winding.

No. 131,026; for in a shell-type transformer there are two flux paths in parallel, each enveloped by three turns for a $1\frac{1}{2}$ turn winding, as shown in Fig. B. The author considered an extension of this method to 4, 6 or 8 flux paths in parallel (Fig. C) and, although it was quite correct and feasible on paper, manufacturing and practical difficulties ruled it out as a commercial proposition. Mr. Sayers will note that the claim made in the paper for this method was that of more economical proportions of active material. The notes with reference to the core and shell type methods of construction seem to have created a controversy. These notes were not intended for that purpose, but were inserted to show the possible adaptation of the two types to the special design required for furnace transformers. The author does not hold any brief for either type, but if a consensus of opinion of furnace transformers in use in this country were taken one would find that well over 90 per cent are shell type. Mr. Sayers's experience of core-type transformers for power work may have been good and the author does not doubt it, but the illustration he gives is no indication as to the core type being

preferable to the shell type. Similar cases to that quoted could be given relating to shell-type transformers, and possibly transformers for much higher voltages than those referred to by Mr. Sayers, which were probably only in the neighbourhood of 6,000 volts. His remark that the shell type would have been hopeless is evidently not founded on fact or experience, but on prejudice. Mr. Sayers evidently wants to see all the coils of his transformer. If he does see them—and, by the way, only the *outer* parts of the coils of a core-type transformer are visible—what advantage is there to be gained? From experience, the proportion of failures after several years of service is very much higher for the core type than for the shell type, hence the life of a shell-type transformer can be said to be longer than that of a core type.

In reply to Major Taylor, the author does not state in the paper that the reactance is almost entirely in the connections, but that the lay-out, which includes the furnace and connections in *large installations*, is a source of high reactance. As it is hardly possible to reduce the reactance or loop area in the furnace, that part which can be amended must be given attention, hence the connections between the transformers and the furnace are discussed. The booster transformer will not in itself improve the power factor of the circuit, but it will probably increase the efficiency and permit of equal loading of the parallel low-pressure coils under all voltage ratios. The suggestion that the booster be excited from one of the other phases has not been considered, it would probably improve the power factor to some extent, but the additional switchgear and cables necessary would increase the cost and operating difficulties. The author does not think that the supply frequency between 25 and 50 periods materially affects the furnace operation. 50-period supply is used on the majority of furnaces in this country, but that is simply due to the supply being of that frequency in the districts in which the furnaces are located. There is one advantage of the lower frequency, namely, that the inductance drop in the leads is lower due to the drop being proportional to the frequency with a constant current. Major Taylor's concluding remark that the author does not seem to like Scott-connected transformers is in a measure correct, and for the following reason—Scott-connected transformers are apt to be abused and their life impaired when used with two-phase furnaces. A two-phase furnace with a conducting hearth has one phase across each electrode to the bath, i.e. it has a voltage V across the electrodes to the bath and a voltage $\sqrt{2}$ V across the electrodes. If the hearth becomes non-conducting, as it does at times when a new lining is put in the furnace, then the load comes across the two electrodes in series and a single-phase load comes on the supply mains. Although from the low-tension ammeters this single-phase current appears to be quite normal, the primary loading is seriously unbalanced. The teaser winding carries full-load current, and half of the main transformer carries approximately 50 per cent and the other half 150 per cent load. From the above it will be seen that if half of the main transformer be allowed to carry 50 per cent overload for a long period it will be seriously overstrained and its life shortened. As ammeters are rarely used on all three high-tension phases the above unbalance is rarely noticed, and furnace transformers having a Scott connection are therefore liable to misuse in the above sense. Scott-connected transformers are quite satisfactory if loaded correctly on the two-phase side.

The author would direct Mr. Fedden's attention to the paragraph headed "High-Pressure Terminals" on page 202 of the paper, in which he suggests that individual terminals should be used for line leads. As most furnace-transformer specifications call for all leads to be brought out, this is done by bringing the tappings out through terminals separate from the line leads. The author does not suggest that the 8,000 k.v.a. be embodied in one transformer but in one group comprising three single-phase transformers each of one-third capacity. This will assist the lay-out and be easily handled and located. Mr. Fedden's remarks *re* experience of lay-out trouble confirms the author's statements in the paper. The Scott-connected transformer has already been referred to above. If well designed, it is quite a perfect method of transforming three-phase to two-phase power, provided that the loading is two-phase and not single-phase. Mr. Fedden's experience of mechanical stresses must have occurred in some way other than normal operation and possibly it was a very small plant with little or no protection or reactance in circuit. In a small plant additional reactance is necessary, as the lay-out carrying low currents would have a low inductive drop. The example in the paper is for a large plant carrying heavy currents. The method of obtaining additional reactance mentioned by Mr. Fedden is no doubt quite effective, but is very extravagant, the losses being very high, and in many cases it becomes a very noisy and hot piece of apparatus. This method is generally used as a remedy for a furnace equipment that has been designed with too little reactance in order to save expense and violent load fluctuations.

Mr. Mercer is quite correct in his assumption, so far as the paper deals with experience. However, since electric furnaces have only been in use some 8 to 10 years in this country, it can be said that only recent experience has been dealt with. During the war period, furnace transformers were called upon for heavy duty, in many cases for service for which they were never intended. This heavy duty in several cases resulted in failure, and the experience gathered from these failures has been of service both to the furnace designer and to the transformer engineer. The author is in agreement with Mr. Mercer when he says that transformers of too low a rating were ordered for furnaces, and especially those for Scott-connected groups as already explained. Negligence on the part of the user has been the sole cause in several instances of failure, as Mr. Mercer states. The author has not included in the paper any gear or apparatus concerning the furnace alone, as the subject under review was furnace transformers and not furnace equipment. The furnace control has certainly been improved, but there is still room for further improvement.

In reply to Professor Smith, internal reactance is essential in furnace transformers in order to steady the arc. The value depends on the size of the furnace

and the lay-out. With 2-ton furnaces an internal reactance of 10 per cent is in general used, while with larger sizes 5 to 6 per cent. As the size of transformer and furnace increases, the author considers a heavy internal reactance to be unnecessary, since the reactance of the lay-out will meet all requirements. Professor Smith's suggestion that the core type is preferred to the shell type because it is easier for the teacher to demonstrate that type, is a very weak argument. If everyone preferred the easier of two alternatives, progress would soon cease. It is quite possible to design a core-type furnace transformer with one or two turns, provided the core section could be made large enough for sound construction. The transformer could also be made with concentric windings and the reactance obtained as suggested. The objections would be those of cost, difficulty of construction, and adequate cooling. If a booster scheme were suggested for the author's comment he would divide the required reactance between the transformer and booster in such a way as to have minimum losses resulting from that reactance.

In reply to Mr. Cowie, the mechanical stresses possible in a core-type transformer would not be any heavier than those present in a shell-type transformer of similar size and characteristics. However, since the coil surface of the coil of a core type is much smaller than that of a shell type in the usual design, the stress per unit coil surface would be greater for the core than the shell type. With regard to efficiency, the core type would be slightly lower, for, as stated on page 205, the copper loss or load loss is rather heavy, and the efficiency would be approximately 0·2 per cent lower for a 750 k.v.a. transformer. It is difficult to give comparative figures owing to the many variables possible, but the above will act as a guide. The figures of cost on page 213 include the cost of the cooling equipment such as cooling coils in the transformer tank, and also in the case of force-cooled transformers the cost of piping and oil cooler and pump, but excluding the piping and water-supply mains. Mr. Cowie's last remark is hardly clear. If he means an odd number of turns I agree, but if he means a half turn as described in the paper I fear he is mistaken, and at any rate the Patent Office did not know of such an arrangement.

Mr. G. E. Taylor's experience *re* tappings has been unique. The author's remarks have, however, been confirmed by several speakers, and he does not therefore propose to say anything further except that he does not wish to convey the opinion that the actual tapping point of the coil is always the trouble; other items such as congestion due to tappings and complex switchgear sometimes give trouble. The author agrees that the reactance must obey the linear law, but this is only necessary within the possible load-current limits as far as the furnace is concerned. Mr. Taylor's somewhat contradictory statement of the power factor of a furnace is hardly convincing. If he were to measure the power factor during the melting period by means of a recording voltmeter, ammeter, and wattmeter, I think he would find that 0·8 is a fairly good average figure until the molten stage is reached.

Mr. Clothier refers to the failure of the insulation of transformer terminals and suggests that these should receive more attention. The author thinks that Mr. Clothier has misread the paper, for on page 201, at the bottom of column 2 it states: "Failure of insulation of switchgear and transformer terminals on the high-pressure side due to the heavy auto-transformer effect in consequence of the large range of voltage." In the paper the author also states how this cause of trouble has been eliminated by re-arrangement of the high-pressure windings. The suggestion that totally enclosed high-tension conductors should be used is quite straightforward on paper, but if looked into in detail the possibility of catering for a large number of leads, possibly 24 or 30 in number, puts an entirely new complexion on the case. Naturally Mr. Clothier as an expert in this type of gear looks at it from his point of view. The comparative low voltages used in this country and the equitable climatic conditions, together with the extra cost this enclosed gear would involve, make its universal adoption a debatable point.

Mr. Holbrook agrees with the author on several points that have been brought forward in the discussion, such as tappings, ratio, reactance and location. With reference to ventilation, it is very difficult to give figures as required by Mr. Holbrook, as so much depends on locality. The inlet air should be led in on all sides, or directed to all parts of the chamber. The outlet also should be in or near the roof so that the air has a direct upward flow. Two apertures of approximately 2 ft. × 6 in. on each of the four sides at the base and roof should be ample. The author agrees that transformer chambers are in many cases badly ventilated and in inaccessible places and that they have frequently resulted in the short life of a transformer. With reference to the efficiencies of the transformers shown in Figs. 1 and 2, since the efficiency varies with different ratios that of Fig. 1 is of no value, and as regards Fig. 2, the author's remarks in reply to Mr. Cowie will cover the point. Mr. Holbrook has stated the case of core type versus shell type in the author's own phrase. In connection with transformers for furnace work, the shell type adapts itself better to the many requirements. This is the author's experience, gained in the design and manufacture of a large number of transformers of this type. With reference to Mr. Holbrook's diagrams and circular coils, the pro's and con's of the case are many and cannot all be dealt with. Circular coils are only advantageous when the mechanical stresses possible are radial as they are in concentric windings, for in this case the major forces are radial. In a shell type the major forces are axial and on the coil surface and so do not distort the coils as the diagram suggests. Mr. Holbrook's remarks in connection with Fig. A are somewhat misleading, especially to the lay mind. If alternating current be passed through a free solitary coil in air, i.e. one having only an air core, then when carrying excessive currents the coil will be extended to its maximum area. This is not the case, however, in a transformer under short-circuit, i.e. when excessive currents are flowing through it, for in this case the ampere-turn fluxes are neutralized in the magnetic core and only the leakage flux is left, which is distributed between the two adjacent coils or groups of coils of reversed polarity. This leakage field in a shell-type transformer is at right

angles to the axis of the coils, and hence the mechanical stress produced is in line with the coil axis, and so not radial. This being so, a rectangular coil used in a sandwich shell-type transformer cannot be distorted in a radial direction due to excessive current. Rectangular coils wound on modern lines are not at all as shown in Fig. A, and when wound are tight and the long sides are parallel.

I agree with Mr. Ashdown that the future of the electric furnace in this country is dependent on the supply of cheap power, and unless this is available we shall not see a very rapid progress in electric furnaces. However, other countries on the Continent and in America have this cheap power available, and hence British engineers must endeavour to keep up with the times and supply equipment for those fields. The author's suggestion of trial furnaces on page 207 does not mean a large equipment, but a small equipment built on similar lines to the large furnace. The author made tests some time ago on a special equipment suggested by a furnace manufacturer and the results obtained proved the impossibility of the suggestion, but at the same time revealed another method which was entirely successful. Progress is not attained without research and financial risk.

In reply to Mr. Stobie, the transformer shown in Fig. 2 is one in which all the leads were required out of the case. There are four bushings; through the two outer ones the line leads are brought individually, while the tappings for voltage regulation are brought through the other two in multiple, four through one and five through the other, and these are lead directly to the regulating switches. Mr. Stobie's experience of flash-over between terminals 6 and 8 inches apart must have been due to dirty conditions or to bad contacts and vaporized metal or oil. His excellent operating results without interleaving are quite possible with only 7,500 amperes, but are dependent on the relative position of the transformer and furnace and on the type of furnace. The furnace evidently had no conducting hearth and the transformers must have been directly on the furnace bed or below. It is not always possible to locate the transformers adjacent to the furnace, and if so placed they have to be carefully watched and kept clean and artificially cooled. The disadvantage of a regulating transformer, as stated by Mr. Stobie, is not convincing. Mr. Stobie fears radial stresses, but, as already stated, they do not exist in sandwich-type windings unless the coils are out of balance or the tappings are short-circuited, and in a case of this sort no radial bracing however strong would be of any service. The possibility of a 30- or 40-ton furnace, as suggested in the paper, is evidently in line with Mr. Stobie's idea of future development. The possibility of increasing the voltage of the furnace transformer by having two arcs in series is certainly a welcome advance, but this will entail a large number of electrodes as in case 1, and the starting up with one arc and the other electrode short-circuited will, in the author's opinion, lead to heavy starting currents, as the starting arc will have double voltage and hence double intensity and current.

DIRECTION AND POSITION FINDING.

By Captain H. J. Round.

(*Paper first received* 31 *December*, 1919, *and in final form* 9 *March*, 1920; *read at a* Wireless Sectional Meeting *of* The Institution, 14 *January*, 1920.)

Preliminary.

The major portion of this paper is confined to a sketch of the war development of direction and position finding as far as it was known to me.

The general ideas involved in wireless direction-finding and position-finding are fairly well known now, but I have thought that it would be better to give an elementary introduction to the subject in order to make the paper more complete. This introduction will simplify the discussion afterwards of various side issues which have become important in the practice of the art.

General reception.

For consideration an electrical wave can be divided artificially into two components, the electrical and the magnetic components.

In an ordinary electrical wave these two components are at right angles, and the direction of travel of the wave is at right angles to both of these components.

If we take a conductor such as a wire, and place it in the field of the wave and parallel to the electrical lines of force, the field applies a voltage to the wire and the wire attempts to destroy the field.

Obviously, however much the field was moving (consider the limiting case when the wave-length is very long), if its strength remained the same no useful result would be produced in the wire, but if the field varies from time to time, a varying electromotive force results in a varying current in the wire and, from this varying current, energy can be obtained in outside circuits.

A wire at right angles to this electrical field has no electromotive force induced in it.

For certain reasons these fields are usually made to vary with a simple harmonic motion, and the result on a conductor placed in the right direction is a simple harmonic electromotive force.

The resulting currents, and the phases of these currents in these conductors, depend on their electrical constants, which again depend partly upon their mechanical dimensions. If the conductor is fitted with inductance and capacity adjusted to be in resonance with the simple harmonic motion of the wave, the currents in the conductor will be in phase with the applied electromotive force.

If the inductive reactance is predominant, the current will lag. If the capacity reactance is predominant the current will lead relatively to the applied electromotive force.

If instead of considering the effect of the electrical field on the conductor we consider the effect of the magnetic field, that is, the number of magnetic lines cutting the conductor per second, producing a certain applied voltage, we are talking about the same thing, but sometimes this will give a clearer mental picture of what is happening.

Directional reception.

If two similar conductors are chosen parallel to the electrical lines of the wave, but spaced along the direction of propagation, it is easy to see that the currents produced in them will differ in phase, and if we algebraically add these currents by means of some such arrangement as in Fig. 1, we can produce new effects.

The single conductor we have been considering will have no knowledge of the direction of the wave motion because, from whatever the direction the wave is coming, the currents produced will have the same amplitude, provided the electrical force of the wave remains parallel to the conductor.

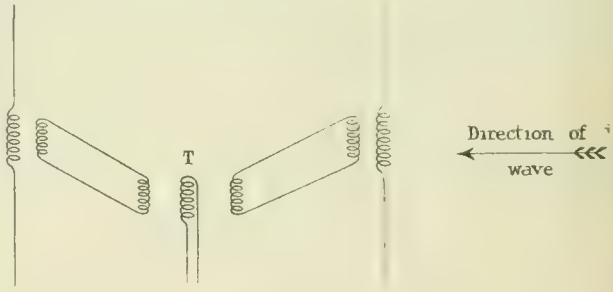

Fig. 1.

The currents in the two conductors, if added algebraically in a certain way, will, however, enable us to determine the actual direction of the wave, although we shall have still no knowledge of what is called the sense of that direction.

Suppose in Fig. 1 we actually subtract the two resultant currents by making the two conductors of electrically the same constants, and subtracting on a transformer T placed half-way between the two. Then we can easily see that a wave coming from the direction of the plane of the two conductors will not produce currents of the same phase, except in a few particular cases when the distance between the conductors is 1, 2, or more wave-lengths exactly, and consequently a resultant current will be left.

But if the direction of the wave is at right angles to the plane of the two conductors, the two currents, then being exactly in phase, will balance and no resultant current will occur.

Every other direction of wave will have a resultant current.

Fig. 2 gives the well-known polar diagram of reception on such a system. I have marked the two halves of this figure positive and negative for the following reason.

If the subtraction of the two currents is examined with regard to the phase of the resultant current, it will be seen that the phase remains the same throughout each circle, the current merely altering in amplitude, but the phase is completely reversed in the other circle.

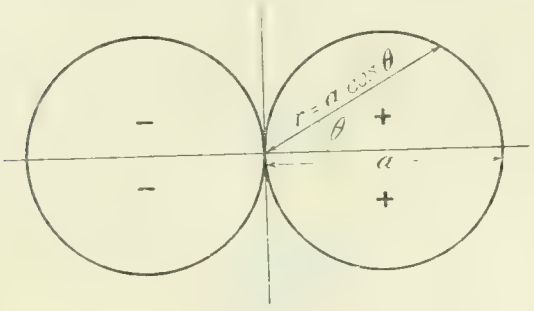

Fig. 2.

Such a system as this, if we could arrange to shift the two conductors on a circle round an axis between them, would enable us, by plotting the curve of Fig. 2 for any wave, to determine the direction of that wave; and obviously, if we had somewhere a standard of phase, we could also get the sense of that direction by using the reversal of phase through the zeros.

In such a system as these two conductors, we are not limited to the simple subtraction of currents in

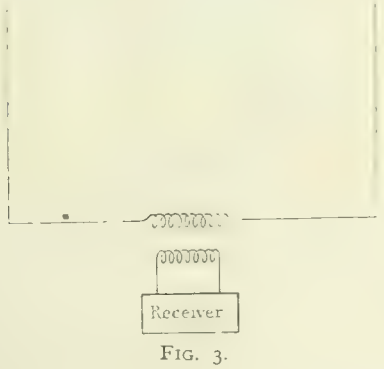

Fig. 3.

the conductors. We can misphase our currents in the conductors and add them, or obtain the same final result in still other ways.

This system of two conductors would be very difficult to use in practice if the distance between them was great. Obviously to bring them nearer together will give a weaker resultant current, but this is actually done so as to enable the conductors to be easily moved on a common axis. To avoid the complication of transformers, other methods of addition or subtraction are used.

A simple bent conductor with resonance arrangements at T (Fig. 3) is one form of combined conductor suitable for direction-finding. The conductors may, however, be joined at both top and bottom (Fig. 4) and the well-known frame aerial made up. Or a large number of conductors can be arranged in a circle with switching arrangements to switch to any opposite pair, or finally the well-known Bellini-Tosi method may be used to enable four conductors to be added together in such a way as to give the effect of a rotated pair.

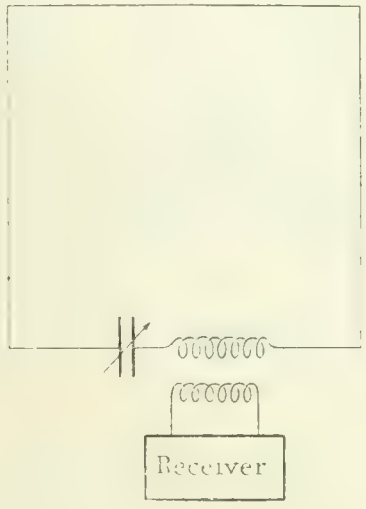

Fig. 4.

Effect of earth.

Before, however, describing this last method, I will introduce the question of the earth in directional reception.

If a straight copper wire, A (Fig. 5), is pointed directly at a source of waves, and there are no other bodies near to distort the fields, no longitudinal currents will be induced in the wire except those of a second order, due to skin effects.

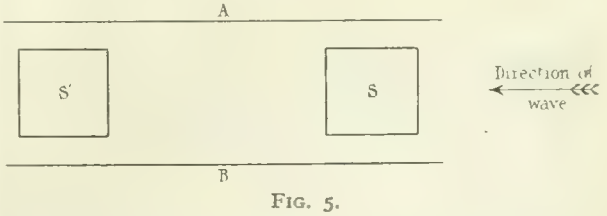

Fig. 5.

If another wire, B, is placed parallel to A, this also will have no currents induced in it. Neither of these wires will cut the magnetic lines.

But if a conductor S is placed between A and B at one end, the magnetic lines can now cut S, and the resultant difference of potential in S at its ends will induce in A and B an electromotive force which will result in currents in both A and B. If we replace the conductor S by a substance usually called an insulator, which has a greater dielectric capacity than ether, then if the dielectric current can be assumed to be made up of the displacement current in ether, plus elastic motion of electrons, currents will also be induced

in A and B; but whereas in the case of a leaky dielectric or conductor the motion of the electrons is partly inelastic and the energy of the motion is partly lost, in the case of an imaginary perfect dielectric no energy will be lost in the dielectric.

Such a system it will be seen is not, however, directional; because, from any direction, the wave will induce the same electromotive force, but if we place another conductor at S′ the result, it is easy to see, is a directional receiving system similar to the frame of Fig. 4, because when the direction of the wave is at right angles to the plane of the wires A and B the electromotive forces induced in S and S′ are equal and opposite in their action on the conductors A and B, and other directions of wave give the diagram of reception represented in Fig. 2.

It is almost obvious that such a system can be replaced by a single horizontal wire above the surface of the earth, and even under the surface, depending on the conductivity and dielectric constants of the ground.

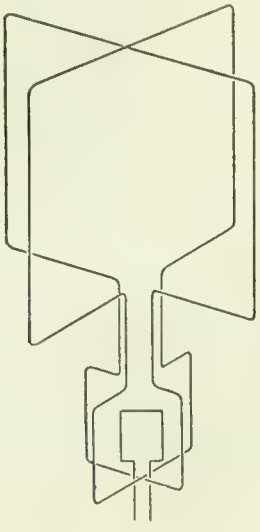

FIG. 6.

Of course, if one considers the final currents produced in such a circuit, their values will now be determined partly by the conductivity and dielectric constants of S and S′, and it is not immediately obvious what the values of such currents are.

An element of this earth effect undoubtedly occurs in reception even on frames, but it is probably minimized by keeping the frame away from the earth's surface as much as possible, and of course it will usually be approximately uniform in any direction.

Cosine diagram.

Returning to the two vertical conductors or the frame receiving aerial, it is now obvious that the electromotive force in such a system depends upon the angle which such a frame has to the direction of the wave. It can easily be shown that if the frame's dimensions are small compared with a wave-length, this electromotive force is proportional to cos ϕ where ϕ is the angle of the plane of the frame to the direction of the wave (see Appendix 1).

Bellini-Tosi aerials.

In practice the operation required to draw the polar curve may be difficult if the frame is fairly large—in other words the mechanical means for turning it will be cumbrous. So resource is had to a method of combining the effect of two frames placed with their planes at right angles to one another, the plane of each frame being vertical to the earth. This is done by connecting a piece of apparatus to the two frames so that in this piece of apparatus a miniature but concentrated duplicate is made of the original magnetic field of the wave, the only difference being that as now there is no electrical field, we are not actually dealing with a wave in motion. But if the electrical wave now shifts its direction through an angle ϕ the magnetic field will, in the subsidiary piece of apparatus, shift

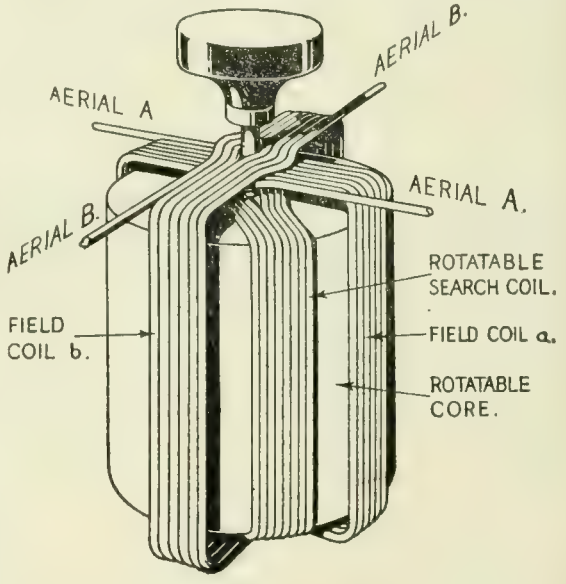

FIG. 7.—Diagram illustrating arrangement of coils on the direction-finder.

through ϕ degrees also. Consequently we can place in this miniature magnetic field a small frame an inch or so in size and determine the polar curves of various stations.

The simplest way of making this apparatus is to wind two coils at right angles as a miniature of the big aerial frame system, and to connect each of these two coils to an aerial. If we imagine each coil is placed parallel to the aerial frame to which it is connected, and the connections are the right way round, it will be seen that the miniature magnetic field is parallel to the main magnetic field of the wave.

Of course, there is no actual necessity to place the apparatus in this position, but, curiously enough, in the avoidance of certain errors, it has sometimes been found advisable to do so. This piece of apparatus invented by Bellini-Tosi is called a radiogoniometer. Fig. 6 shows two aerials and the coils to which they are connected, and Fig. 7 the two coils with the small rotatable frame.

Determination of sense.

There is one other point that is of interest in direction-finding work, and that is the determination of the sense as well as the direction. I have noted that the two loops in Fig. 2 represent currents opposite in phase, and that any method of determining this difference of phase will give the sense. It is clear that, if a single straight conductor is erected at the centre of such a frame, the phase of the electromotive force in it will be independent of the direction of the signal. Therefore if we can combine the currents in this aerial and the frame so as to detect the phase change on the frame we can read off the sense.

I have noted in Appendix 1 that these two currents are 90° out of phase, the vertical current representing the electrical field of the wave, and the frame representing the rate of change of the field, so that, to combine these currents so as to produce a zero of addition at any position, a mis-phasing operation has to be done on one aerial. For instance, the frame may be tuned and the vertical aerial left untuned.

Now if we obtain a zero reading from a signal in one direction by adding together the effects on the frame and vertical aerial, a rotation of the frame through 180° gives a phase shift in the frame of 180°. As the phase in the vertical aerial is unaltered, we shall get an addition of the two aerial currents instead of a subtraction. Instead of rotating the frame, the rotation of the transmitter round the receiver gives the same effect; consequently we are enabled to determine the sense of the direction of a station.

It will be seen that even if the phases of the frame and the vertical aerial are obtained correctly, unless the strength is obtained correctly also the zeros will not be opposite the maximum. Fig. 8 represents a series of diagrams obtained by the addition of various strengths of signals in the frame and the vertical aerial. These will be of interest in a later part of the paper dealing with instrumental errors. Some of these diagrams were obtained by Marconi on his original horizontal aerial experiments.

Practical question of taking readings.

In practice such a process as plotting the cosine diagram from a station is impossible. Time is usually against one, and the question is introduced how, with some aerial arrangement such as described, can the direction of the wave be read?

An examination of Fig. 2 shows that both maxima are very flat, that is, a large change of angle round these maxima gives a very small change of strength.

The zero of strength is extremely sharp, and theoretically if one determines directions by observing the position of this zero the best results should be obtained, but several limitations enter here;—

(1) The signal zero extends over an angle owing to weakness.

(2) As will be mentioned afterwards the actual zeros are very often indefinite.

(3) Any jamming is, at this point, liable to interfere with the signal more than at points where the signals are strong.

For all purposes in the present state of wireless, I must assume that telephone reception will be used. The loss of the characteristics of a signal which any recording method necessitates is too great a loss to be balanced by almost any conceivable other advantage of recording, except possibly in very particular cases where a great strength is being dealt with, or wave-lengths are being used which are far away from the normal field.

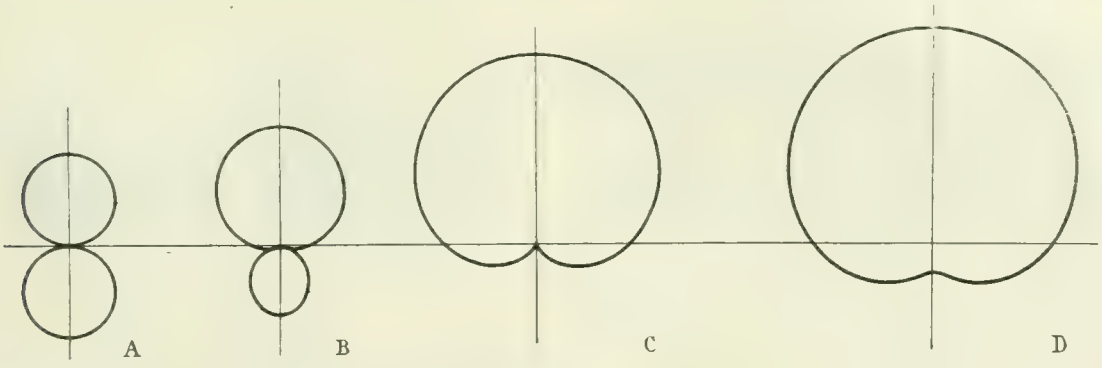

FIG. 8.

Instead of reading the zero position an alternative is to read two positions of equal strength, and this is, and always has been, done in practice.

In ordinary frame or Bellini-Tosi practice, the operator swings his moving coil to two positions giving equal strength, and assumes the zero or maximum lies half-way between the two positions. Depending upon circumstances, he may swing through a narrow angle or a wide angle. It is a simple step from this to arrange two coils swinging together, with a change-over key to change from one coil to the other, so as to obtain again equality of strength.

This latter method which was tried out long before the war was again attempted with modern gear, but in practice, although possibly giving slightly more accuracy with untrained men, it was rejected because it was slower to use than the swinging by hand, and one always had to make sure whether the swinging was being done round a minimum or a maximum. Also the variable

angle of swing was not easy to arrange while ensuring the accuracy of placing of the coils.

The Royal Air Force used this switch on aeroplanes, but instead of arranging two frames at the necessary

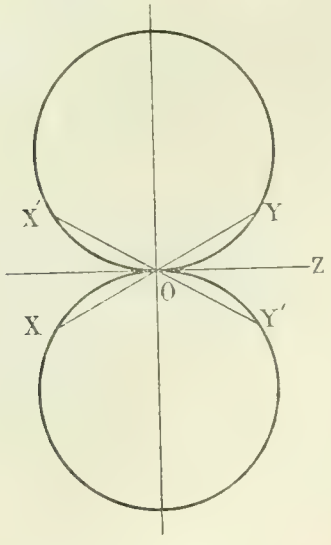

FIG. 9.

X Y and X' Y' represent the two positions of a rotating frame or a rotating search coil of a Bellini-Tosi set to give the two equal strengths O Y and O Y' required by the operator to determine the direction O Z of the minimum of signals.

angle, they took one frame and added to it a frame at right angles, connected first one way and then the other way. This is obviously the same thing. The

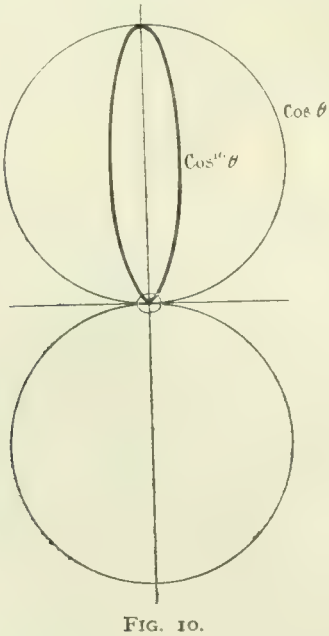

FIG. 10.

angle between the equivalent frames is altered by altering the ratio of the sizes of the two R.A.F. frames. I have not so far, even on aeroplanes, found the necessity of using switching arrangements, the operation being easily performed by hand swinging of the search coil, but possibly in the future it may be introduced on navigational stations when other sources of errors are eliminated.

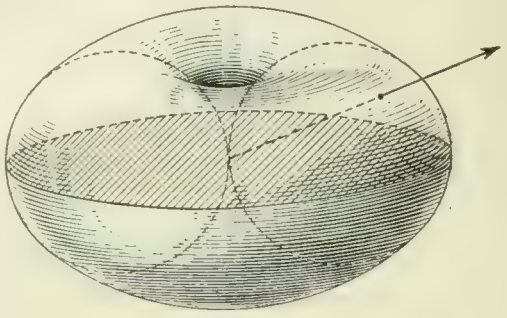

FIG. 11

I have mentioned that to read the maximum is not directly possible on account of its bluntness. It is rather interesting to speculate whether it is possible to obtain a sharp maximum.

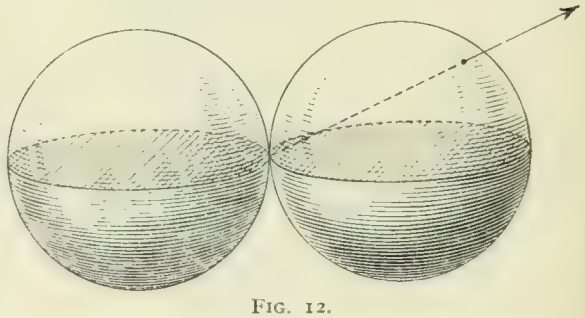

FIG. 12.

One can only imagine the production of a real ray effect by covering with receivers a great area of wave front. But I can conceive of an apparently sharp maximum being produced by some successive application

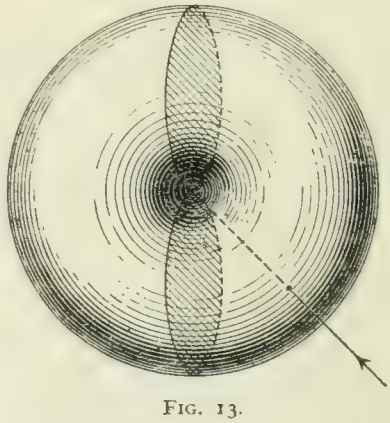

FIG. 13.

of a power law to the original current, say by rectifying the original current through a square-law detector, reconverting this into high-frequency current, and rectifying again (Fig. 10); also by sliding back the

potentiometer with a valve detector, and then amplifying afterwards. Exactly what would happen with such a scheme with jamming stations of different strengths is very doubtful, and one great advantage of the cosine diagram would be lost, for, with a real maximum system, it would be necessary to have an independent stand-by scheme with which to hear stations, but the cosine diagram is, with an occasional shift of the pointer, good enough as a stand-by.

The diagrams of reception that have been discussed so far have been those in a horizontal or an equatorial plane. In order to be able to study the various errors that affect direction-finding, reference must be made to the solid diagrams of reception of the three types of aerial systems that have been referred to. Fig. 11 is the solid diagram of reception of a vertical wire. It will be noted that as the signal gets nearer and nearer to the vertical direction the signal strength falls off according to the cosine diagram, so that when the signals are quite vertical the receptive power of the aerial is zero. Fig. 12 is the solid diagram for the aerial shown in Fig. 1. In this case the receptive power of the aerial system is zero in the vertical direction, and also in the horizontal direction when this horizontal direction is at right angles to the plane in which the two aerials lie. Fig. 13 is the solid diagram for the frame shown in Fig. 4. This diagram is of the same shape as that for the vertical wire, but in this case it is placed on edge. It will be seen that the receptive power is no longer zero in a vertical direction, but only in a horizontal direction when such direction is at right angles to the plane of the frame. The difference between the diagram of the frame aerial and that of the two vertical aerials becomes of importance when considering night variations and the aeroplane error.

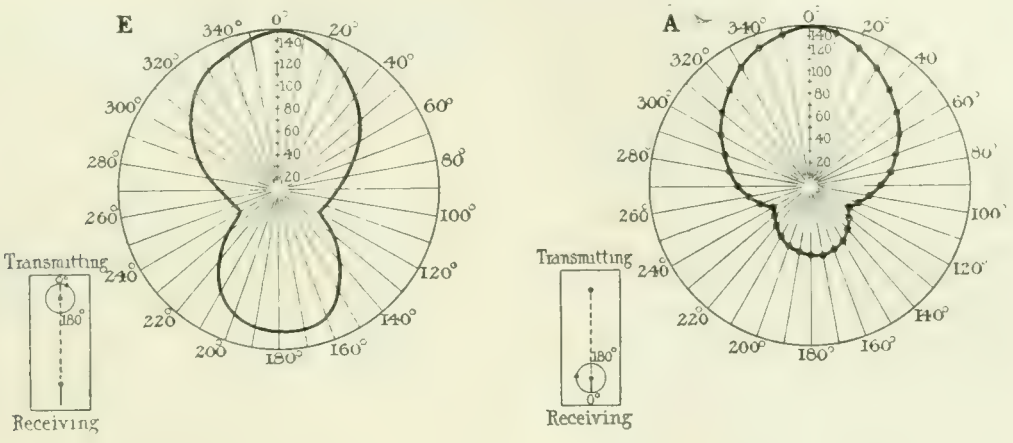

FIG. 14.

HISTORICAL SKETCH OF WAR-TIME DEVELOPMENT.

It would probably start a controversy to go too closely into the original conception of directional reception. Fitzgerald, before Hertz, suggested frames for radiating, and probably, with his insight into things, noted possible directional properties. Hertz undoubtedly recognized directional properties in his receiving loop, but this was one which was not very well closed. All this was before Marconi's original work with vertically polarized radiation.

In about 1899, 1900 and 1901, S. G. Brown and others suggested the use of spaced aerials for the purpose of obtaining non-circular radiation. The frame aerial was probably first suggested by Dr. Lee de Forest. In 1906 Braun combined aerials to give heart-shaped diagrams.

Marconi determined the radiation curves (Fig. 14) of bent and long horizontal aerials, and arranged the first direction-finding system which utilized the position given by signals when at their maximum strength. That directional reception was a practical proposition over short distances in 1905–1906 I can testify, because on Long Island, N.Y., in about 1905, I did a large number of experiments with multi-turn receiving frames using a magnetic detector in series with them. Signals were received over distances up to three miles from a plain aerial transmitting station. The insensitiveness of the detector eliminated any possibility of practical use, and after various tests, which included the addition of vertical aerials and frames to produce heart-shaped diagrams, but which did not include any conception of the Bellini-Tosi scheme, the tests were dropped.

Artom suggested and used a directional method, but the indefiniteness of the original description prevented any clear conception of his ideas.

Bellini-Tosi schemes revived the subject, and the system began to have a practical form when Major Prince, in 1912, modified the Bellini aerial to complete frames. The Bellini-Tosi idea was so complete that one might say that all work after the original conception consisted in carrying out correctly the idea and in the improvement of the receiving apparatus. The sensitiveness of the crystal, although greater than either the magnetic or electrolytic detectors, still limited the ranges of reception very greatly on directional aerials.

In 1913–1914 I had in operation short-wave wireless telephone sets using three-electrode valves for both transmission and reception. The development of simplified receiving circuits using these valves, utilizing both high-frequency and low-frequency magnification, sug-

gested the revival of the radiogoniometer for war purposes almost immediately after war broke out.

Early war trials.

Early in September 1914 possible uses of direction-finding began to be evident to us, and we decided to try to improve the Bellini-Tosi arrangement so as to increase its accuracy and range. A Bellini-Tosi aerial system was erected on a 70 ft. field station mast at Broomfield. Standard Bellini-Tosi radiogoniometers were connected up to the receiving gear which was arranged to use either (1) crystal only, or (2) valve plus crystal. I was very doubtful whether, when using the valve, reaction effects would not cause serious trouble, but fortunately this did not appear to be the case. Other troubles, however, did appear.

Owing to the short distance over which it was possible to receive signals on a frame when using only a crystal as a detector, none but the very strong stations could be received. It had been, therefore, usually impossible to obtain a large number of readings with which one could check the accuracy of the radiogoniometer. When starting work with the valve plus crystal, I found great divergence between the observed and true directions. In every case where it was possible to do so, directions were taken when using (1) crystal only, and (2) valve plus crystal. In each case the observed directions agreed, which pointed to the fact that the errors were probably not due to the valve. Finally, nearly all errors were put down to two causes :—

(1) A coupling between the two aerial systems not due to the search coil. This gave maximum errors in the plane of either aerial.

(2) Incorrect tuning and consequent mis-phasing of the two aerial systems. This gave maximum errors in the plane of 45° between the two aerials.

The first difficulty was overcome by setting out the aerial systems accurately and by more accurate manufacture of the radiogoniometers. The second, by abolishing the double condenser, which pretended to tune the two aerials simultaneously, and by using two separate condensers. Tuning and phasing was done by means of a small buzzer transmitting radiogoniometer coupled to the aerial systems.

The correction of the first error, until quite recently, always gave us trouble, particularly with short waves. This was owing to the electric coupling between the two aerials. Incidentally the methods of checking that this coupling was zero were rather troublesome.

Another series of errors appeared afterwards, due to badly constructed aerial tuning condensers and to very puzzling dielectric losses. The condensers first used had ebonite as the dielectric, and any small difference in the internal losses was swamped by the large internal loss. Other dielectric losses, such as those in walls and tables, were not noticeable until later. This was when the aerials were made larger with respect to the wave-length, and the potentials at the ends of the aerials consequently became higher.

The introduction later of condensers having air as the dielectric gave trouble. This was owing to the type used being a built-up aluminium-vane condenser. It was found practically impossible to avoid resistance in the condenser, as the contact to the aluminium vanes could never be made perfectly good. We therefore reverted to brass vanes solidly soldered up, and after this all trouble vanished from a condenser resistance point of view.

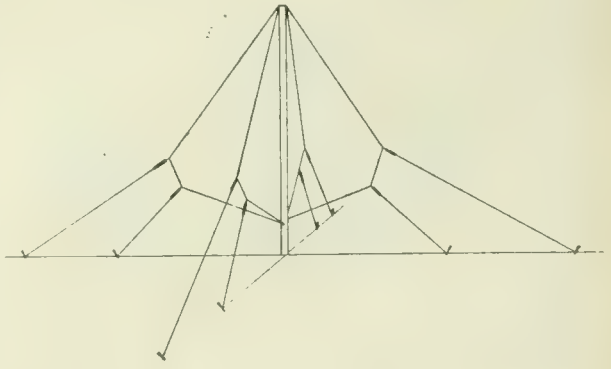

FIG. 15.

Aerial systems used.

The first aerial systems were small diamond-shaped frames, supported on 70 ft. wooden masts (Fig. 15),

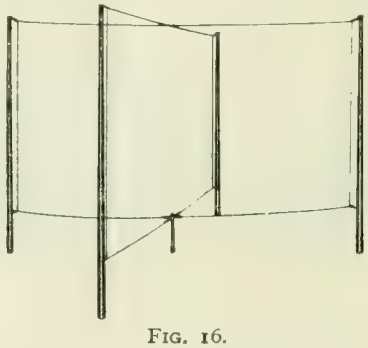

FIG. 16.

the corners of the diamond being guyed out by ropes. A little later on, in the days when wood was still cheap, we erected four masts and put up square

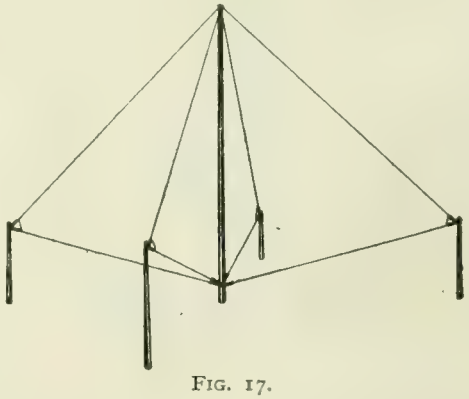

FIG. 17.

frames (Fig. 16). This seems to be the best form of aerial for general all-round accuracy. Still later, on account of the cost of masts, we reverted to the diamond-shaped frames with one high central mast and four small corner masts (Fig. 17).

Multi-turn frames were seldom of any use in the Bellini-Tosi work ; a condenser could always be inserted to tune up one-turn frames and, of course, direct connection with the aerials, as in rotating frame work, is not required. Multi-turns, even if used in parallel to reduce inductance, have the disadvantage that the inductance varies in windy weather.

A few dimensions are appended of single-turn frames for the various wave-lengths chiefly used :—

Wave-length	Shape	Height	Diameter
200-400 metres . .	Diamond	50 ft.	50 ft.
400-800 ,, . .	(1) Square	60 ,,	60 ,,
	(2) Diamond	90 ,,	90 ,,
800 upwards . .	(1) Square	120 ,,	120 ,,
	(2) Diamond	170 ,,	170 ,,

Any larger sizes than these became difficult to handle, owing to the self-capacity of the frame becoming large compared with that of the tuning condenser. Actually, with modern amplifiers these frames give all that can be required in the way of signals.

Insulation and leading-in.

Insulation is not an important function because, in wet weather, all insulators get wet about equally and

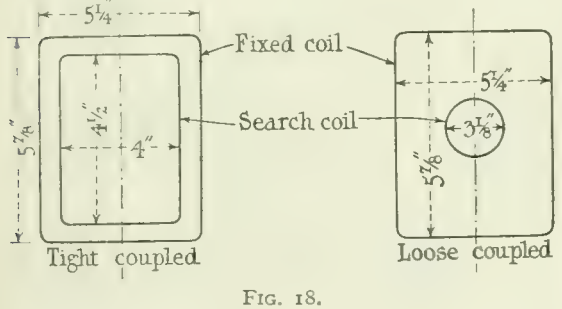

FIG. 18.

the effect on the two aerials is about the same. At the same time it is preferable to avoid any chance of inequality by using long lengths of porcelain at all suspension points.

The leading-in of aerials is a very troublesome process. The lead-in wires from the central mast have to be firmly fixed with regard to one another, and yet if they are supported rigidly from the mast to the building the latter becomes very noisy due to the mast vibration being transmitted to the walls of the building. Insulation at this point is more difficult to maintain than elsewhere and is more important, as the building is liable to shield one set of aerial insulators more than the other.

The buildings were usually placed in an angle between the legs of the two aerials, and this resulted in a capacity coupling between the aerials which was negatived by a small condenser connected across one of the legs of one aerial and the opposite leg of the other aerial.

Radiogoniometers.

During the war we made practically no alterations in the dimensions of the radiogoniometer coils designed by Bellini, except in the number of turns on the windings, for as originally designed they produce a very small error, and to have eliminated this error would have taken a great deal of work, which was not necessary in view of more serious errors.

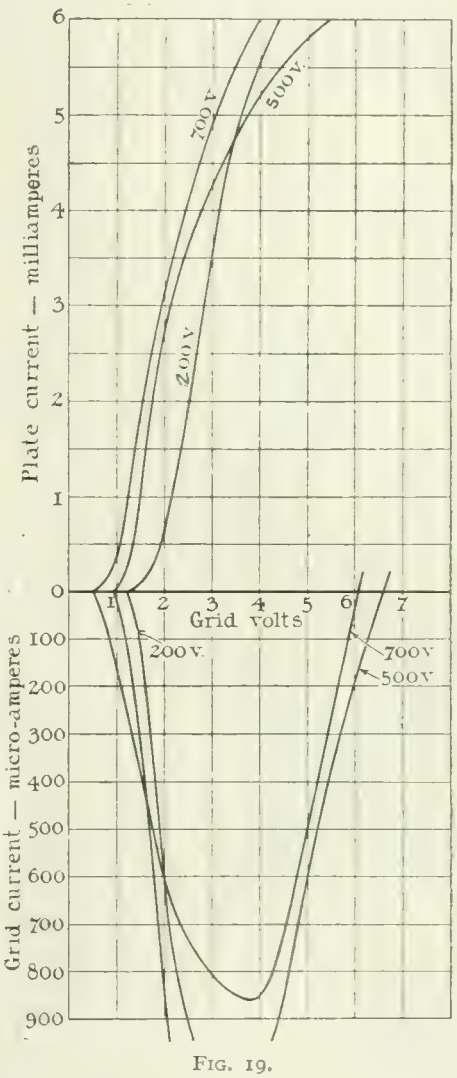

FIG. 19.

Two dimensions of coils which we used for different circumstances are shown (Fig. 18), viz.

(*a*), which we called " tight coupled," and
(*b*), which we called " loose coupled."

Actually both types were tight coupled, for in each case the coupling when at a maximum with one aerial alone was more than that required for maximum signals, if aerial and search coil were tuned to the same wave-length.

Almost at once we discovered that in war the enemy does not send on one wave-length only, nor does he send

V's when requested, and many were the schemes evolved both for tuning to his wave-length and for taking his direction rapidly, say, all in the space of a few seconds. The difficulty was enormously increased by the extreme care with which the aerials had to be balanced. After a little experience we found that if the aerials were tuned to, say, 800 metres and carefully balanced or phased, then by retuning the intermediate and final circuits, but without altering the aerial tuning, signals could be received with only a slight falling off in strength, from 200 metres below to 200 metres above this tune, that is from 600 to 1,000 metres. This was due to the above-mentioned tight coupling of the radiogoniometer.

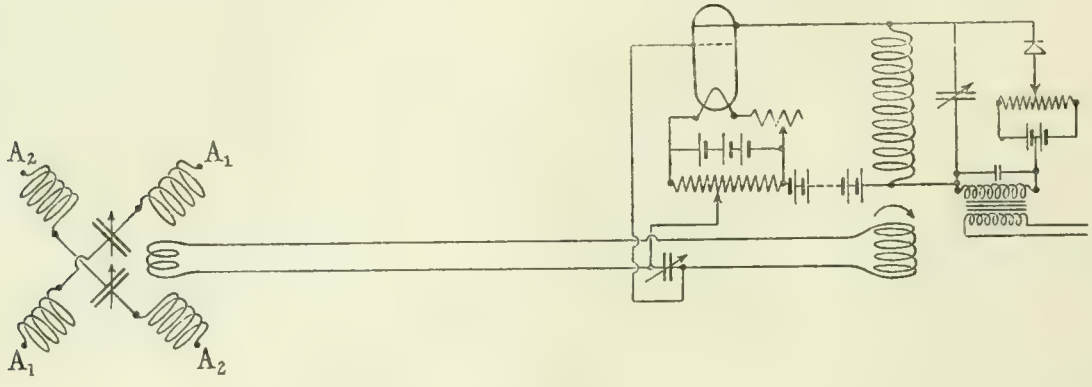

FIG. 20.

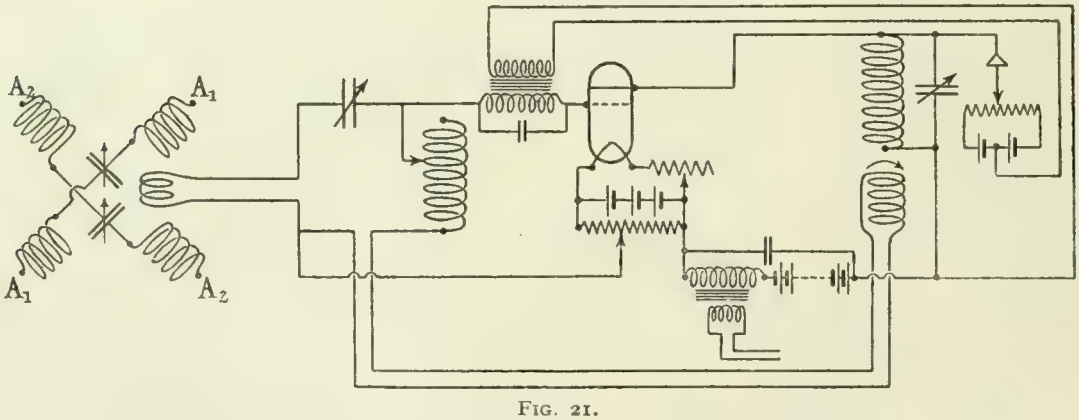

FIG. 21.

Some attempt was made to use Mr. Russell Clarke's scheme of linked condensers. This scheme was, however, not extensively tried; for the reaction coil had to be readjusted continuously in order to keep the set near the oscillating point, and it was found that if the final jigger coils were made of sufficient length, they also worked over a big range without a condenser in parallel with them. With only the reaction coil and intermediate condenser to handle, operators became very expert at searching over considerable ranges of wave-length. They rapidly found out the German rule for change of wave-length, and the various wireless signals which indicated these changes.

Later on, with modern amplifiers, all these things became easy, but in the early days they caused much trouble. After the German rules for wave-length changing had been determined, quick searching only became necessary when these rules were being changed, and also in a few other cases.

First valves and circuits.

Aside from the above-mentioned errors, other errors were not at first serious. I had modified Franklin's reaction circuits for spark reception to give simpler tuning arrangements, and these circuits, when added to the Bellini-Tosi system corrected as above, made a very good direction-finder which at that time was of extraordinary sensitiveness. It was probably fortunate in the first year of our work that we used the soft valves, because no hard valve has been constructed which can compare with these "C" type tubes as high-frequency magnifiers. They necessitated, however, trained men in their manufacture, and trained operators for their efficient use.

I give here a characteristic of a "C" valve for those who care to compare it with that of a modern hard tube. If the "C" valve characteristic (Fig. 19) is compared with that of a hard tube, the comparison will show that the "C" valve is equal in magnifying power either to 16 hard French tubes in parallel, or to three in cascade. Actually in practice, when used by

a skilled operator, it is better than three in cascade in an amplifier having aperiodic intervalve connections. Some of the apparent amplification shown by the characteristic is actually not obtainable because, on account of grid conductivity, a rather large ratio of capacity to inductance is required in the grid tuning circuit. The use of this large ratio of capacity to inductance in the direction-finding receiving gear accidentally avoided for us the serious error known as "vertical," which was afterwards obtained with hard tubes, and it was very fortunate, for we had quite enough other trouble to contend with at the time. With the "C" valve the average high-frequency magnification when using reaction was about 150. With high-frequency magnification the receiving power of the frame and Bellini-Tosi system at once became almost equal in value to that of the vertical aerial.

If an aerial system is taken and high-frequency amplifiers attached to it, a practical limit of amplification is reached when jamming and X's become too strong. In practice, therefore, it is possible to amplify up frame signals to a strength even greater than those of a vertical aerial, for owing to the frame's localized receptive diagram there is liable to be less interference.

Fig. 20 gives a diagram of one of the first circuits in use. Captain Tremellen was very fond of the ingenious double-magnification circuit (Fig. 21), due to Schlomilch, as was also the original high-frequency magnification without reaction. I usually preferred a single low-frequency amplification after the crystal.

I have mentioned that the production of valves at that time required special men. Even then it was a terrible process. Again and again we lost the knack of making good tubes, owing to some slight change in the materials used in their manufacture. A thorough investigation was impossible, as all hands were out on the stations. On several occasions we were down to our last dozen tubes.

This type of tube had been tested out on long waves at Clifden for quite long runs, and on those circuits they were very steady. The shorter waves, however, necessitated higher values of filament current and lower values of vacua, thereby shortening the steady life considerably. It is, however, pleasant to record that "Methusalah" was removed after 8,500 hours, only to make room for a new circuit with hard valves, and this to the regret of the operators. A good many examples were obtained of lives nearly as long as this.

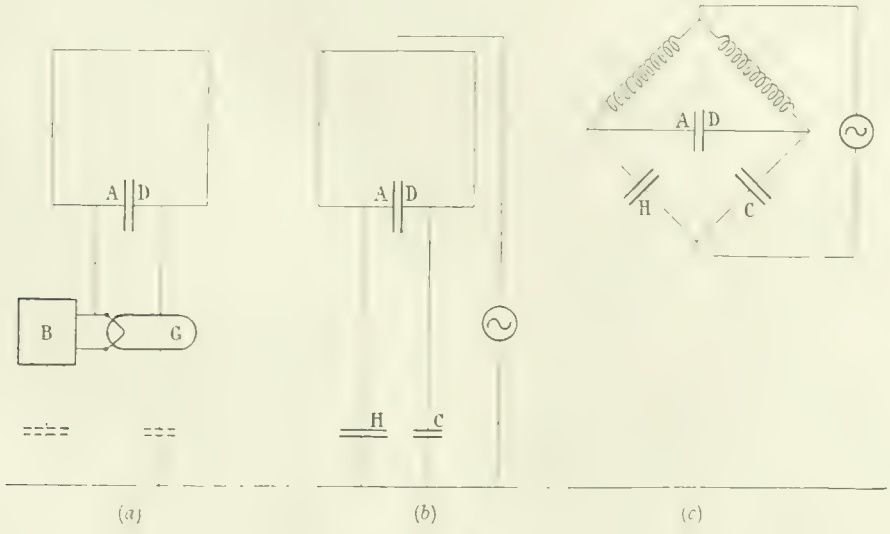

FIG. 22.

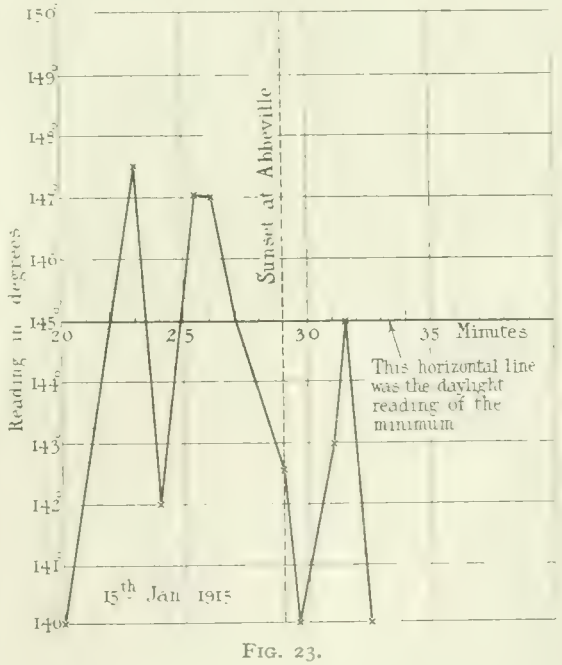
Sunset at Abbeville
Reading in degrees
Minutes
This horizontal line was the daylight reading of the minimum
15th Jan 1915

FIG. 23.

Everything suggests that a long ageing is necessary

to produce a steady valve, unless success is obtainable with a gas such as helium or neon. Curiously enough, a spectrum analysis of an old tube never showed anything but hydrogen, but with hydrogen I was never able to make a tube that was any good. A few tubes were obtained which, after 1,000 hours, would run indefinitely as amplifiers or oscillators without any

nicknamed "Vertical." This error was only small, and save for the determination of its cause need not have been regarded. We noticed that the two zeros shown in Fig. 2 were seldom opposite to one another, even if using only one aerial of the Bellini-Tosi system. This was traced to a small "vertical aerial" receptive power, chiefly due to the difference in the capacity of

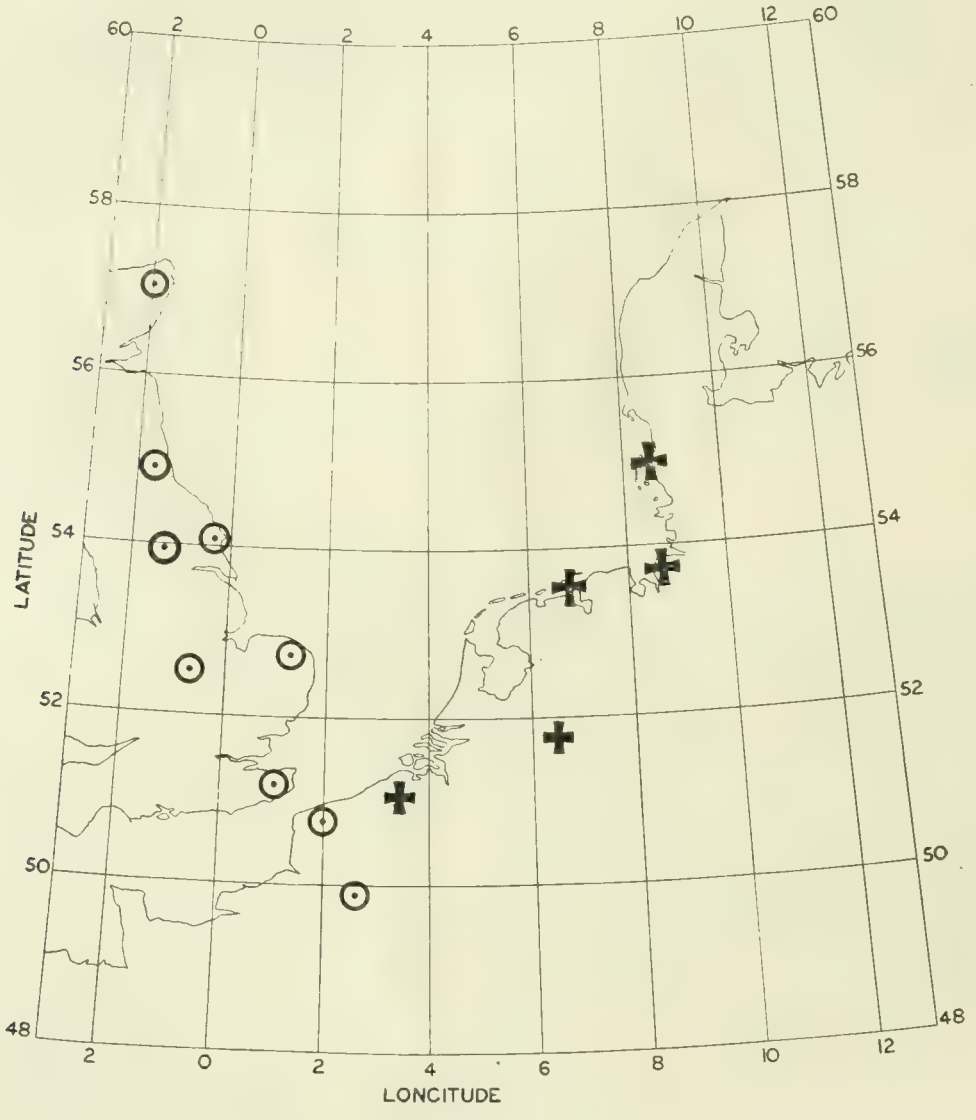

FIG 24.

filament battery. The filament was apparently being heated by the high-tension battery, which was usually 400 volts.

Great credit is due during this period to Messrs. Edison and Swan, Ltd., and particularly to Mr. Copelin and his staff, for the patience with which they carried out my instructions for making the valves.

Another source of error.

Quite early in 1915 another error appeared which we

the grid of the valve to earth, and of its battery to earth. We corrected it at first by adding a small condenser from the grid to earth, the value of the capacity being equal to that of the battery to earth. Owing to the smallness of the error, however, this correction was not often applied.

I can probably explain the meaning of the error by taking the simple case of a frame directly connected to a valve (Fig. 22). Such a frame as shown, if not connected to the receiver, gets current induced in it which

gives a potential difference between the terminals A and D of the condenser. This potential difference is the correct cosine function of the direction. If now a valve grid, G (Fig. 22*a*), is connected to D, and the valve-filament battery, B, to A, the capacity of G is usually small compared with B, and, besides the true directional reception of the frame, there is a reception due to these capacities to earth, I have redrawn this arrangement in Fig. 22*b*, which shows the action of the wave in alternating-current form. Fig. 22*c* shows the arrangement in bridge form. From this it will be seen that unless the capacity C is equal to the capacity H, a current will flow through the condenser A D. The fact that a current flows through the condenser A D means that there is potential difference across the terminals A and D, which is independent of the directional properties of the frame. The result of this circular reception on top of the directional reception is a "cottage loaf" shaped diagram of reception, the minima of which are not opposite to one another. This point has already been brought out and illustrated in Fig. 8.

With the use of hard valves, and the consequent high insulation of grids, these "vertical" troubles increased a great deal, and they increased still more when the "aperiodic" aerial was brought into use. Methods other than the addition of condensers to the grid were afterwards used, for they were more reliable as they required no adjustment. They were chiefly methods of shielding and shunting to earth and will be mentioned later.

Night errors.

So far, I have only touched upon the aerial and upon instrumental difficulties and errors. Probably, it has occurred to some, working on signal strength, that the extraordinary variation of signals at night, so different from the constancy during the day, might be accompanied by variations in apparent direction. I must confess that I had not thought seriously about it.

In December 1914 we erected in France, at Blendecques near St. Omer, and at Abbeville, the first two war direction-finding stations, these making the first position-finding group erected by us during the war. Blendecques, unfortunately, had a fixed daylight error which puzzled us, and not until Abbeville was constructed did Captain Tremellen note that night directions did not maintain the constancy of day readings. The first station concerning which he noticed this effect was KAV, the old German press station, and I am able to show here a copy of his original curve taken of KAV's movements during a sunset period (Fig. 23).

This curve is typical of a sunset movement, but I still cannot say whether any such apparent regularity exists as a general thing, and certainly we were never able to arrive at any system of correcting bearings by using the idea of regularity.

After this first indication we of course noticed that night variation was a general thing, and it remained throughout the war a serious defect in the direction-finding work. I have attempted to set down here a number of facts regarding night effects which may be useful to those building-up theories, but I must apologize for the scarcity of real material.

One must remember that all stations were concentrated on a military and naval object, i.e. Intelligence work, that the stations being watched sent erratically, and seldom at the right time or for a sufficient length of time to make observations worth while, and also that the stations were worked by men not particularly interested in direction-finding as a research. Only long-wave Press stations sent for lengthy periods, and we could not afford to concentrate direction-finding men on watching these stations. However, Captain Tremellen and Lieut. Adcock in France among others, and particularly Lieut. Eckersley in Egypt and Salonica, succeeded in obtaining valuable information, the latter in conjunction with experiments developing the theoretical side. Eckersley is, I believe, preparing to publish his work on direction-finding. The work of these men suggests possible improvements in apparatus which will eliminate a great deal of the night trouble.

We were not the only people suffering from night effects. As is well known, the German Navy directed their Zeppelin fleets by direction-finding from land stations. They also used a method of intercommunication between their land stations by wireless telegraphy. I am permitted to show approximately the positions of the German direction-finding stations and also the approximate position of some of our own stations (Fig. 24). The Germans, in raids on England, suffered from a bad base-line, and this, in combination with night effects, made their directional apparatus useless on many occasions.

An interesting point regarding the night effects was discovered later by Captain Tremellen. The Germans had two radiophare stations for enabling their Fleet and submarines to determine their positions in the North Sea without having to transmit. These radiophares in effect consisted of a rotating frame continually sending during rotation. A signal was sent to give the zero of time, and any ship noting the time interval between this zero and the zero of signals could then determine its angular position from the station.

The fact that a frame transmits vertically as well as horizontally, and that at different points in its rotation the vertical radiation is polarized in a different direction, should lead one to expect curious results at night. Owing to the continuous rotation of the transmitting frame, very strong signals were necessary to take quick bearings at a direction-finding station. Notwithstanding the difficulty, Captain Tremellen was able to note a large variation of the apparent direction of these stations at night as the frame rotated. This was done by reading the minimum on his own radiogoniometer, and not by noting the minimum of signals with his search-coil stationary. Unfortunately these stations have stopped work, otherwise a complete investigation of this would have been undertaken.

Notes on Night Effects.

(1) Large swing readings are better than minimum readings. To obtain readings of the actual minima at night is very difficult, for from spark stations with no definite zero one gets peculiar changes of note, and different operators will estimate the weakest place at

quite different angles. I have attempted to draw in Fig. 25 a representation of a typical night minimum. This effect is sometimes very marked from Telefunken stations. Even with a swing reading, a very distinct difference of note will often be obtained at the positions A and B, the note on the one side having obviously fewer harmonics, i.e. being duller in sound, than the note on the other side. This again adds to the difficulty, and the reason for the effect is not at all obvious. In England and France, errors on swing readings on spark stations are present up to 7° at night, and seldom more, but there are occasional records of errors greater than this. Eckersley's results in the East indicate much greater changes than these; he has told me that at Salonica, Sofia would sometimes shift through 90°.

The directions change fairly rapidly when bad night effects are present. Two or three degrees in a minute would, however, be considered to be fast. Nearly always, but not invariably, night variations are accompanied by bad minima.

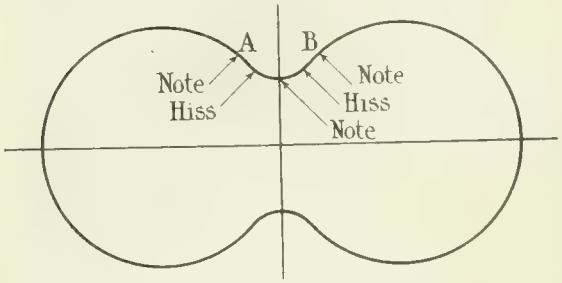

FIG. 25.

(2) Continuous waves give much greater variations than spark waves, and with them it is quite definite that directions are seriously wrong even when the minima are extremely sharp, although bad minima do occur at other times. Captain West brought to my attention a very pretty case of variation which indicates that the apparent direction is a function of the wave-length. Horsea arc station sent its Press programme at 10 o'clock nightly during parts of the war, and it sent with a spacing wave as well as a marking wave. These two waves sometimes gave two directions differing by 30°, each wave giving a perfectly sharp minimum. This point may be intimately connected with the results obtained at San Francisco by Dr. Lee de Forest some years ago on interference effects.

In studying night effects, continuous waves have the advantage in that no annoying change of note takes place, which may cause a doubt as to the exact position of the minimum.

(3) There is no strong evidence to show that the night variations on long waves are greater than those on short. The idea we obtained was that this was the case, but this may have been due to the shorter distances worked over on the short waves, and also to the fact that the amount of intervening land was smaller.

(4) In England, variations from east to west are certainly greater than those from north to south, but I do not think that this result agrees with results from the East and from America. Malta was a peculiar station, which in England apparently never varied seriously.

(5) When signals come over-sea from moderate distances, and practically no land intervenes, results are then the most reliable and can be relied upon for the greater part of the time. If, however, there is land anywhere near either the transmitter or the receiver, or between the two, results become very troublesome.

The minimum distance at which night effects have been noticed in England or France is about 15 miles.

Captain Tremellen noticed quite early, that when two transmitting stations with differently shaped aerials were side by side, the directions obtained at night by a Bellini-Tosi station were different.

Mountainous country between stations seems to give the very worst night effects, and I should think that extremely wooded country would also be bad, but I have no evidence of this.

Theories of night effects.

In the early days I had vaguely in my mind ideas of refraction and reflection in the lower and upper layers of the atmosphere which thereby produce twisting of the wave front. I had also the idea of rotating fields which thereby destroy the minimum. Eckersley's theoretical and experimental work with night effects in the East, and with aeroplanes—also, quite independently, Adcock's work in France on aeroplanes—gave a clue to a part of the trouble at least. These two engineers have both suggested apparatus which should, when developed, improve our work at night. I will give a very rough sketch of this important work, leaving it for them to give exact accounts of their work at another time.

It was noticed that when Zeppelins were well at sea, night errors were not usually serious, but aeroplanes nearly always gave trouble. Experiments were carried out during the day with an aeroplane flying at varying heights, and at different angles to the radius from the receiving station. To see clearly what happens in this case, firstly it must be remembered that the aeroplane, being small and having the aerial flying out backwards, does not usually radiate a wave in which the electrical lines are predominantly vertical and the magnetic lines horizontal. If this vertically polarized radiation only were present, a receiving loop at a distance would receive no signals when its plane was at right angles to the direction of the aeroplane. If, however, the aeroplane is at a height and some of the magnetic field of the wave reaches the loop in such a manner that it is partly vertical in one plane and with the lines leaning forward towards the receiver in the other plane (Fig. 26), a current will be induced in the loop, and the resultant zero position, if the frame is rotated, will be produced by the sum of the two currents due to this effect and that of the vertically polarized wave. It is very noticeable that the error produced becomes negative instead of positive if the aeroplane reverses its direction. A horizontal loop will receive from an aeroplane flying at a height, on account of this twisted field. An aeroplane flying towards or away from a station gives no error.

All the above were daylight results, but it was sug-

gested by Eckersley that this aeroplane-effect was produced at night by the reflection from irregularities in the Heaviside layer, and there is good evidence that this theory is true.

Again, a horizontal loop receives during night variations, and Eckersley has proved experimentally that the strength on the horizontal loop and the night variation agree with the theory in a remarkable way.

In the later stages of the war, night errors from Gothas were extremely troublesome, the only satisfactory times being when they were flying either towards or, preferably, away from the observer.

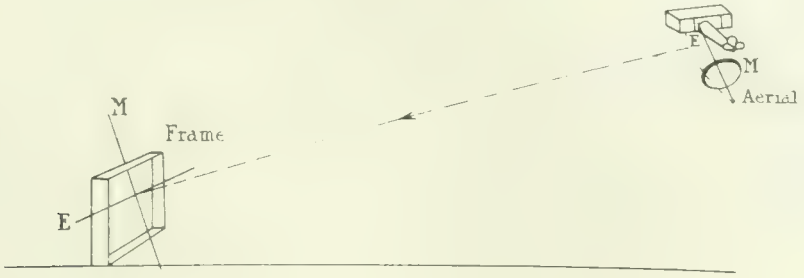

FIG. 26.

DAYLIGHT ERRORS.

Daylight errors, aside from instrumental ones, were much more difficult to notice. They were seldom as much as the possible errors of the instruments.

Apparently it is a bad thing to place stations on the edge of high cliffs, near high trees, or near a wood. One station on the edge of a cliff had an error, as far as one could determine it from check bearings, of an apparently complete rotation through 3 degrees. By increasing the distance of the station from the cliff edge from $\frac{1}{8}\lambda$ to 2λ, the error was completely removed. Another station, also near a cliff edge, gave very curious results. Directions taken of certain stations which were at varying distances, but which were approximately in the same direction, gave the result that directions were correct for certain of the stations but incorrect for the others, and the error went up to as much as 10 degrees.

Refraction over a coast line undoubtedly exists, and Eckersley has obtained a fairly accurate estimate of the refractive index of the coasts of Palestine and Cyprus, this being checked by a large number of stations. This I will leave, together with his night measurements, for his own publication. I have on one occasion in the afternoon noticed the signals from Nauen varying fairly rapidly, but as Nauen was at that time within an hour of sunset the variation may have been a case of night effect. Hanover at the same time was perfectly constant. The presence of hills on one side of a station, even some miles away, tends to give bad daylight minima in that direction.

In connection with all these daylight errors G. M. Wright has, during the last year, been very accurately investigating the more minute instrumental errors which occur, and the probability is that new stations to be erected in the future will much more definitely locate these errors of site, daylight variation, and deflections from the normal.

When one examines the scale of a direction-finder and sees how small a thing 1 degree is, it seems almost impossible that the accuracy we obtained was possible with the number of quite big errors that we had to correct and the many smaller ones we could not disentangle. The extent to which direction-finding was trusted by the authorities was really remarkable, and I can instance one case where a most important event in the history of the British Navy was brought about by an observed motion of less than $1\frac{1}{2}$ degrees in the daytime.

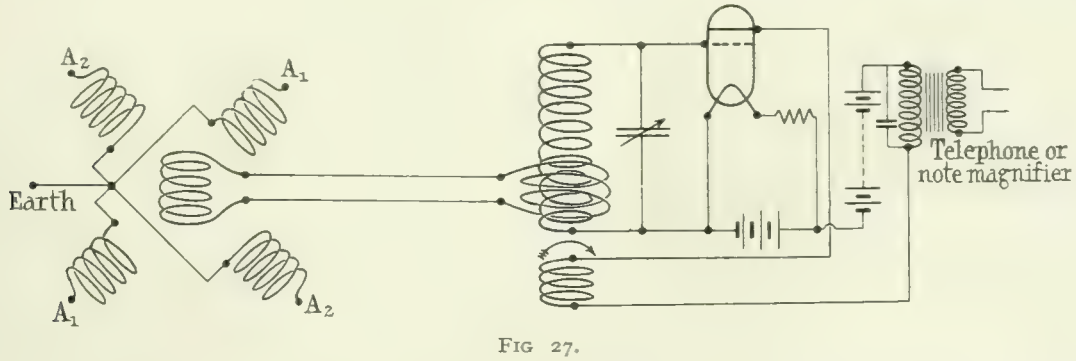

FIG 27.

Practical work.

Groups of direction-finding stations were erected at various places on our coast line, each group consisting

of several stations serving different ranges of wave-length or different types of signals. These groups were interconnected with each other and with Headquarters by land line.

With so many possible errors at night, it was never safe to have only two groups, in fact one gained a false confidence in the beautiful intersections made by using only two stations and only had occasional shocks when the German fleet was found to be well inland. A third station enabled one to know much more definitely if results were of value, and I personally preferred four, the last one being a check on the other three.

A system of good rapid land-line communication to a centre was very essential, and our Post Office in England and the Army authorities in France did magnificent work in this direction.

Besides these groups of stations, many single stations were erected, particularly for submarine work, and very valuable results were obtained. The German submarines were fitted with powerful spark stations working on 400 metres, and I very much doubt whether a signal was ever made by one without our stations recording the position. Of course, it does not mean that in a large area such as the Western Atlantic, if we know the position of a submarine we can sink her, but if we do know her position we need not send our convoys near to her.

In the Mediterranean, which was a great hunting ground for submarines, our direction-finding stations were forced to use a system of wireless intercommunication, and I have heard the story that one Austrian submarine requiring her position, came to the surface, sent signals, waited for us to give her position, and then thanked us and again submerged. This is only to indicate the danger of linking up direction-finding stations by wireless telegraphy.

Short-wave work on rotating frames.

The Bellini-Tosi system is undoubtedly the most rapid and accurate method of taking directions, but many troubles were experienced when we began to need short-wave direction-finders. This was in days before the cascade amplifier came into its own. For short-wave reception under 300 metres it was necessary to use rather large rotating frames, and only just as the war was finishing were we able to tackle waves under 200 metres satisfactorily on the Bellini-Tosi system. The mass of a frame will always be against the use of the latter for good work because, although ultimately there is no real difference between a rotating frame and a Bellini-Tosi in accuracy in clear places, the ability to take an extremely rapid reading makes the Bellini-Tosi infinitely preferable.

With a frame, the balancing troubles do not occur, but the "vertical" error is just as bad and requires just as careful attention. In consequence of the balancing trouble on short waves, Colonel Blandy erected a large number of frames for direction-finding German aeroplanes which were working on short waves, and the work done by these stations in conjunction with the Flying Corps, must have had no inconsiderable influence on the flying side of our campaign. I believe that as many as 11 German spotting-planes were brought down in one week due to the intelligence work of these stations.

One advantage that the rotating frame had to some extent over the Bellini-Tosi was the rapidity with which it could be erected in times of any movement. I rather think, however, that this would no longer hold with the modern "aperiodic" direction finder.

Further Improvements.

In an earlier part of the paper I have indicated that one of our difficulties was rapid searching over long ranges of wave-length. The first real solution of the problem on Bellini-Tosi was indicated by G. M. Wright in 1915, who suggested that the aerial tuning condensers should be short-circuited and a closer coupling made between the search coil and the aerial inductances. A first trial of this method resulted in serious errors and weak signals. I revived the method a few months later for continuous wave work. It was well known that weak continuous waves could be amplified by a low-frequency amplifier, whereas a high-frequency amplifier was necessary for spark signals on account of the fact that a rectifier without heterodyne increases in efficiency with increase of signals, whereas a rectifier with a heterodyne has practically a constant efficiency. Consequently, with continuous waves it was merely necessary first to rectify and heterodyne, and then low-frequency amplify to the extent required.

With spark signals at that time, aperiodic cascade amplification was undeveloped, and the cascade tuned amplifiers we had were impossible for rapid searching on many wave-lengths. In view of this I recognized the possibilities, for continuous wave, of Wright's form of aerial, and it enabled me to obtain a circuit with only one condenser to tune—a particularly necessary condition with continuous waves, as the tuning is so fine.

A previous trial by Wright had indicated that independent heterodyne circuits were troublesome on direction finders because of the unequal action of the heterodyne on the two aerials. Also the addition of the extra heterodyne condenser reduced the simplicity of the one condenser circuit, therefore self-heterodyne circuits were adopted. In the first trial of this system at a coast station I at once noticed again very serious errors and bad minima. This turned out to be the "Vertical" in a greatly exaggerated form. The reason for this exaggeration is that, as the frame is now untuned, the component representing the directional receptive power of the aerial has been considerably reduced, and the component representing "Vertical" reception is now of a sufficient relative magnitude to affect materially the observed direction. A simple solution was obtained which was suitable for all waves above 1,000 metres, and which consisted in earthing the mid-points of the two direction-finder coils.

The minima in the daytime were now very sharp and the directions accurate. With only slight modifications of apparatus this remained our standard continuous-wave apparatus during the remainder of the war. This was also the basis of the "aperiodic" spark direction-finder when the cascade amplifiers were produced (Fig. 28).

Hard valves.

All through the work up to 1917 we had used various forms of soft tubes. I had received early in the war, information and tubes of a harder character from America, but we could not use these as we had erected such a high standard of sensitiveness with the soft valve that in transferring to hard valves we should have lost a lot of useful results. We did, however, in certain cases succeed in obtaining fair sensitiveness with hard tubes by the process of stepping up potentials on the grids to the maximum possible, and by paralleling several tubes.

Cascade amplifiers.

However, Lieut. W. J. Picken succeeded in June 1916 in getting five high-frequency magnifications on 200 metres by tuned circuits with much harder stable tubes, and he obtained such extraordinary magnification that we started to find out how to handle these circuits.

One form of circuit, suggested by Russell Clarke's multiple-tuning circuits, consisted of a number of circuits loosely coupled together with all the tuning variometers moving together. The initial trouble in tuning, and the final narrow range of wave-length owing to reaction oscillating troubles, made the gear only possible for very special work.

In an attempt to get rid of the reaction trouble, we gradually recognized that the real solution of the problem would be in trying not to get too much magnification per valve, and at this point I inserted resistances in all my circuits to damp the oscillations out. The French modification of the audion was by that time in general use, and the French had already constructed resistance cascade amplifiers for long waves.

Any attempt on my part to construct resistance amplifiers failed, and the reason soon became obvious. For waves under 1,000 metres—and we had no living interest in longer waves—the capacity of the valves themselves and of the connections to them formed an impedance which was lower than the lowest resistance that gave cascade magnification.

Colonel Blandy kindly lent me a Latour transformer amplifier; and a careful study of this indicated that my previous cascade amplifier, with resistance to stop reaction, was the right thing, but it had not been taken far enough.

Sufficient ideas were now in hand to start the design of a cascade amplifier for short waves.

Latour's ideas had produced a moderately aperiodic amplifier, but the magnification was still short of the best soft-valve arrangements, and the wave-length was still too long, especially for Army purposes.

The Latour amplifier with iron transformer depended for its quasi aperiodic curves in the large ratio of L/C given by iron-core windings, and also on the damping applied by this iron, as well as that applied by the valves. The first important range of wave-length attacked was for an Army amplifier with a range of from 250 metres to 1,000 metres.

We soon recognized that to obtain a great ratio of L/C the iron was hardly necessary, as coils could be wound with fine wire of considerably smaller self-capacity than the valves and leads.

A three-valve cascade amplifier, built with fine wire coils of one layer, gave a result as good as the Latour amplifier, but the addition of more valves at once caused serious oscillations, and a grid potentiometer became necessary to prevent oscillations, i.e. to give grid damping to the circuits. Valves were then constructed with more open grids and with all capacities cut down to a minimum, and with these valves, four-valve high-frequency magnifiers were constructed, with the new advantage that the plate potential, owing to the more open mesh in the valves, was reduced to 24 volts. Still the aperiodicity was not yet sufficient, and the magnification required was present over a range of only 200 metres.

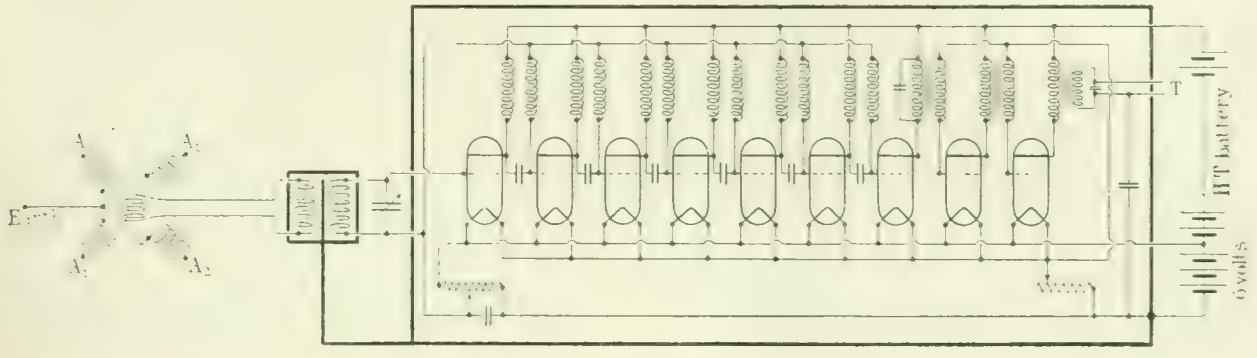

FIG. 28.

The copper inter-valve windings were now replaced by resistance wire wound to exactly the same dimensions, which wire for all ordinary work consisted of No. 48 "Eureka." The set now allowed of the use of six valves plus a rectifier, with practically no adjustments and a flatness of tuning which was almost all, if not quite all, that could be desired. Obviously still better results would be obtained by still greater resistance in the coils and more valves, but seven valves were considered to be quite enough for maintenance of valves and valve current.

The damping applied by the resistance was now of the same order as that applied by the valves themselves, and any variations in valve constants were balanced, so that one no longer had the condition

given by copper coils, which was that one valve would make the set oscillate and another would not.

A further set was made up from 400 metres to 2,000 metres by using longer coils, and the much more difficult range of 100–300 metres required by the Army was then attacked.

The coils required were now so short and the valve capacities comparatively so much more, that the damping provided by the No. 48 "Eureka" wire was insufficient to give, without the sets oscillating, the required magnification and range of wave-length.

At this point Messrs. Edison and Swan offered to draw nickel-chrome wire down to 1 mil in thickness for me. The resistance of this wire for the same length is about 3½ times that of No. 48 "Eureka." This was very satisfactory and a very good degree of flatness was obtained with the seven valves over the range of wave-length required.

The magnification is not so good as the longer wave sets, but it was a very great improvement on anything hitherto produced.

Still shorter wave sets have been produced with this wire. Of course the shorter the wave-length the narrower the range which can be obtained, but cascade sets with a range of from 30 to 50 metres can easily be produced if such wave-lengths are ever required.

Using this wire with coils wound of the same length as the first amplifier mentioned, a set of 11 valves has been made of approximately equal sensitiveness from 250 to 10,000 metres; the higher values being obtained by using the resistance potential drop across the coils, and the shorter wave magnification, as before, being due to the neutralization of the capacity effects by the inductance.

Both the initial and maintenance expense of such a set rather prohibits its use at present, and actually such a range of wave-lengths is seldom required.

Many sets were made up for special work, a standard set of 11 valves being used for short waves in which the damping of the valve circuit was less than the extreme values used above, because only narrow ranges of wave-length were required. This set had a voltage amplification at 200 metres of 2,000 and when more magnification was required, two sets could be loosely coupled together without running into oscillation troubles.

"Aperiodic" aerial spark sets.

"Aperiodic" amplification was now all that could be desired, a rather heavy consumption of valves and valve current being the only disadvantages. I may mention that at one group of Naval stations a pair of 7 h.p. charging engines were found necessary, and 130 valves were running continuously.

Almost at once, quick-search one-condenser aperiodic direction-finders came into use for spark waves. I must admit, however, that an operator is absolutely insatiable with regard to signal intensity. As the "aperiodic" aerials gave slightly weaker signals than the tuned ones, although these signals were far stronger than those given by the old gear, one usually found the operator with the tuning condensers inserted in the aerial in order to get the last fraction of signal strength.

With the introduction of the "aperiodic" direction finder, we found that direct reception on any of the coils in the receiver was introducing slight errors. In the case of the search coil of the radiogoniometer, this can be avoided by placing the radiogoniometer in a correct position on the table. In the case of all other coils, it is avoided by metal shielding.

Fig. 28 shows the arrangement, finally arrived at, of the spark-wave direction-finder. The metal shield inserted between the windings of the transformer is an effective method of avoiding "vertical," except on waves under 400 metres, when in addition it is necessary to earth the centre of the aerial. The diagram shows nine valves; six of these are for high-frequency magnification, the seventh for rectification, and the last two for low-frequency magnification.

Direction finders for 200 metres, constructed with 11 or 22 valves in cascade, enabled us to watch with ease certain "buzzer" intercommunicating sets, and this with no more error than on the longer wave sets. In these 22-valve sets, 11 valves were connected with quasi aperiodic transformers, a loose tuned coupling was then inserted, and another 11-valve set added. In addition, usually one or two low-frequency amplifiers were added at the end. I measured the total high-frequency magnification at about 500,000.

I stated that the continuous-wave direction-finder was very litle changed after the first set; actually, however, high-frequency amplifiers were used for two reasons. First, a self-heterodyning cascade amplifier is, for some not obvious reason, much less subject to microphonic noises than is a single valve; and secondly, the amount of continuous-wave current produced in the aerial by the self-heterodyne is very considerably less in the case of a cascade amplifier than in the case of a single valve. This enables stations quite close to one another to search over overlapping ranges of wave-length without howling at one another.

Operators.

A curious fact in connection with the introduction of the fool-proof direction finder was that the operators were rather unhappy with them. In the early days, when potentiometers, resistances, and a multitude of condensers had to be adjusted, time passed easily on watch, and an element of competition entered into the game as to who could get the best valve adjustments. Now all that vanished and they were reduced to mere operators again.

I cannot say too much for the high standard of all the operators with whom I came into contact. The keenness of the men really made a doubtful art successful. I have sat through a busy time with Zeppelins, and watched the great speed at which the men took readings, one single swing being sufficient. With my own ear trained to judge signal strength and equality I could never criticize their readings.

Some of the men showed very great interest in the growth of the subject technically, and many valuable suggestions came from them. Some of them became excellent amateur mechanics, and two in particular made for me all the original cascade amplifiers. Others concentrated on Intelligence work and gave many

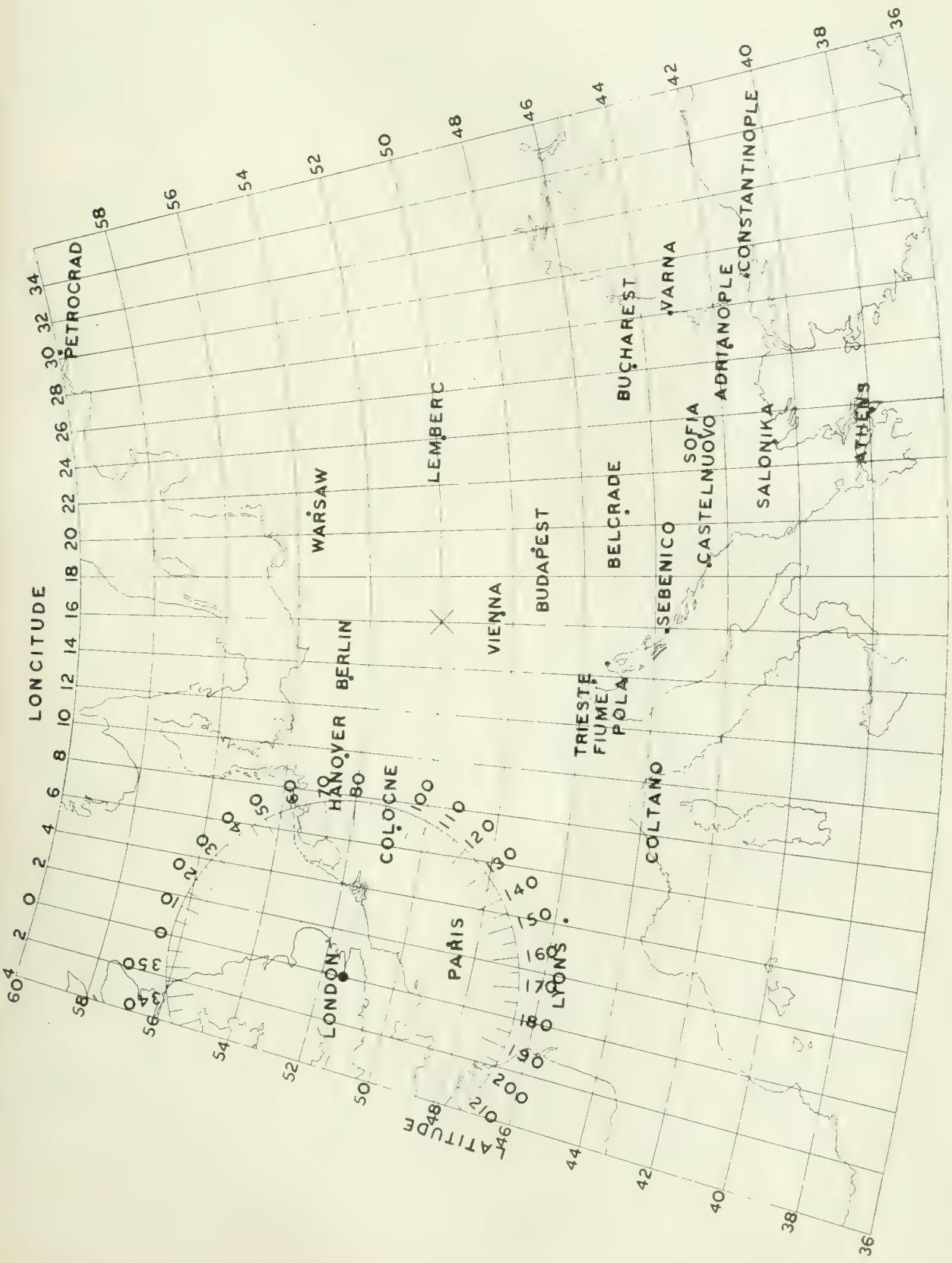
LONGITUDE
PETROCRAD
WARSAW
LEMBERG
BUCHAREST
VARNA
CONSTANTINOPLE
ADRIANOPLE
SOFIA
CASTELNUOVO
SALONIKA
ATHENS
BELGRADE
BUDAPEST
VIENNA
SEBENICO
BERLIN
HANOVER
COLOGNE
TRIESTE
FIUME
POLA
COLTANO
PARIS
LONDON
LYONS
LATITUDE

FIG. 29.

valuable suggestions as to what further work we could do.

I have seen it stated that of those engaged in technical work in the war there are many who would like to meet their opposite numbers in the enemy camp, in order to compare notes. One general feeling amongst the Naval Intelligence operators, I know, is to meet the one operator who controlled the German Zeppelins and warships. They always imagined it was one particular man who was a super-operator. On several occasions with 9 or 10 Zeppelins in a raid, all frantically trying to communicate with home for bearings or otherwise, wireless occasionally got into a horrible tangle. At that moment the super-man would arrive, take control, and in a twinkling all would be peace and order.

Maps.

In certain side lines direction-finding required investigation work, more particularly in map production. In the first few months we used Mercator charts with great circles every 5 degrees drawn through each of our stations. These were very troublesome to use. A great improvement, due to Lieut.-Colonel Simpson, Captain Edmunds, Mr. J. St. V. Pletts, and the Royal Geographical Society, came when map projections commonly called "gnomonic projection" were produced specially for our work. In these projections, the great circles are straight lines and directions are correct for one point and very nearly correct for points over a large area.

A simple way to consider this type of map is to imagine the shadow thrown on a tangent plane to the globe by a candle at the centre of the globe. It can then be seen that the shadows of all great circles are straight lines and that all angles at the tangent point are true. With the aid of these maps and various ingenious strings, springs and weights, Headquarters could keep up rapid and continuous plotting of the tremendous mass of direction-finder readings coming in during busy times from the many stations.

If one wanted to work from a station very much away from the tangent point, it was sufficient to have round the map a protractor calculated for that point. A gnomonic projection of Europe is shown in Fig. 29.

Atmospherics.

An interesting side line on direction-finding work was its bearing on X-stopping. I can give, however, very little data on this subject. During daytime, on one or two occasions, the positions of thunderstorms was approximately determined and checked, but this was not often possible. At night time, particularly in spring and autumn, X's exhibited very frequently —in fact most of the time in England—a sharp direction which varied a little round the position of 165° E. of N.

The minimum is often extremely sharp, exactly like a well-defined station. It was suggested—I believe by Mr. Cave of the Meteorological Office, Farnborough—that this direction was curiously near the magnetic meridian and perhaps it may be possible to determine if freak signals, and consequently X's, have more tendency to be reflected along the earth's magnetic field, by the Heaviside layer. Unfortunately, observations in other parts of the world are not yet collected.

We were able to use this direction of X's for intercepting purposes, as it was fortunately almost at right angles to the direction of the Heligoland Bight. Signals on a vertical aerial, absolutely inaudible owing to X's, were clear without X's in a frame roughly placed at 75° E. of N.

Frame aerials.

One is often asked about reception on a frame aerial, what circuits should be used, and what is the number of turns that should be used for any wave-length. If the frame required is large, and if it is proposed to use a coupled circuit to the detector, a one-turn frame is as good as anything else, provided one has enough capacity in the condenser to tune it up to the necessary wave-length, and that one takes care of the resistance losses of the wire used and the losses in the condenser.

If the frame to be used is small, very often the leading-in wires have an inductance of the order of

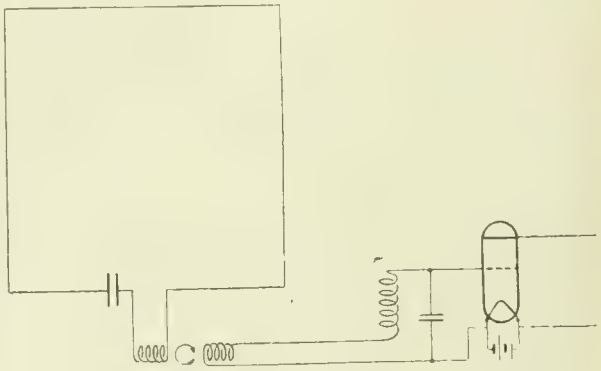

Fig. 30.

the frame. This results not only in a reduction of signals, but in a diagram of reception which does not agree with the frame diagram, if the leading-in wires enclose an area which can receive. Consequently, in this case it is advisable to put more than one turn on the frame. If direct reception is required on a frame, and this, as far as sensitiveness goes is the most efficient method, then with all modern amplifiers with a non-conducting grid circuit the frame should have the maximum number of turns and the smallest condenser which the receiver will take. This limit is usually defined by the amplifier oscillating beyond control.

The previously mentioned correction for "vertical" should then be applied. In loose-coupled circuits most of the "vertical" trouble can be avoided by allowing the aerial only to induce magnetically on a few turns inserted in the transformer secondary between the filament battery and the main transformer secondary.

This is indicated in the diagram (Fig. 26), where only one valve in the amplifier is shown.

Direction-finding on ships and aeroplanes.

Quite early in the war several ships of His Majesty's Navy were fitted with direction-finding apparatus, but

no good chance to investigate errors on board ship really occurred till early 1918. Even before the war, it was well recognized that there was a tendency to give errors which crowded the readings towards a fore and aft direction. Mr. F. P. Swann in a visit to the Fleet suggested that a series of error curves on various warships should be obtained, and Commander Dorling of H.M.S. "Warspite" succeeded in obtaining

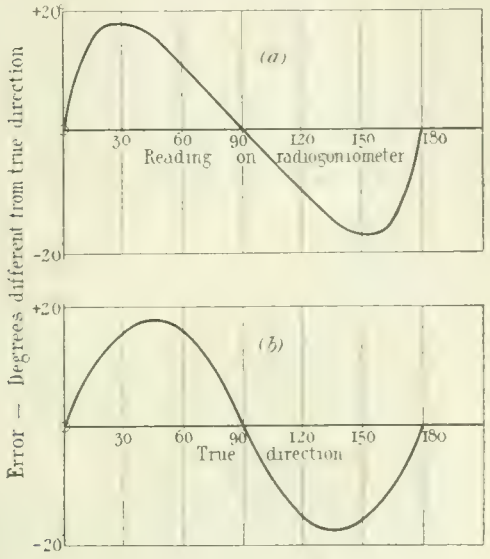

FIG. 31 (a) and (b).

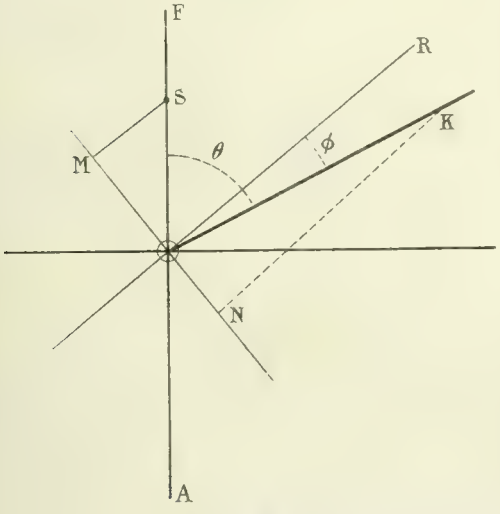

FIG. 31 (c).

a very large number of readings on the "Warspite" and produced an error curve. I append this curve (Fig. 31*a*). The crowding of all the readings towards the 0° and 180° directions, i.e. fore and aft, was very troublesome for taking readings, and we decided to attempt a modification of the Bellini-Tosi system to correct these errors, which amounted in other cases to as much as 30°. After some tests I produced a modified form of the Bellini-Tosi system which enabled me to correct these errors.

Only since the Armistice have I had an opportunity of trying out direction finders on aeroplanes. The four-engine Handley-Page, which went to Newfoundland, was fitted with an extemporized Bellini-Tosi, using an aerial system exactly as on board ship. One aerial was lengthwise round the wings, and the other lengthwise round the fuselage (Fig. 32). A correction which was made on the ground was found to hold good when the plane was in the air. An eight-valve long-wave amplifier set gave very satisfactory signals. Magneto noises which were extremely bad owing to the large number of magnetos, were overcome by shielding the magneto leads and, what was more important still, by shielding the complete receiver system with the exception of the aerials. When the engines were running all out, almost complete silence could be obtained. This set was used effectively in the flight from St. John's to the United States, during which flight directions were taken on Clifden. Similar machines have been fitted since, and the same satisfactory results obtained.

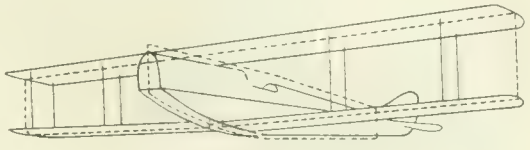

FIG. 32.

I believe the chief use made of the corrected Bellini-Tosi system for ships was in convoy work, but previously the Tenth Cruiser Squadron and other ships had used it during cruising.

All this later work on ships was done with Wright's inductive loop aerial or "aperiodic" aerial, and Wright has during the last year developed an extremely small and practical ship direction-finder for use with this type of corrected frame (Fig. 33). It is intended to apply the necessary corrections on every ship, with periodical examinations of the corrections when the ship is in port, exactly as a ship's compass is treated.

One advantage a warship has over most merchantmen is that there is fitted a gyro compass with repeater compasses, one of which can be near the direction-finder. If no gyro compass is fitted, the exact direction of the ship is extremely difficult to get simultaneously with the reading taken on the radiogoniometer, especially if the ship is turning or yawing. A useful addition to a ship's direction-finder would be a magnetic compass repeater.

Fig. 31*a*, which is approximately the original error curve of the "Warspite," was obtained on a Bellini-Tosi system consisting of two frames each placed at 45° to the fore and aft line of the ship. In the first form the shape of the curve was rather puzzling, because the error was plotted against the readings. On replotting the errors against the true directions (Fig. 31*b*), the curve became a sine curve. The following consideration may indicate how this error arises:—

Referring to Fig. 31*c*, let F A represent the fore and aft line of the ship, and suppose that the ship acts as a very big receiving frame placed in the direction F A. Let O K be the direction of signals of strength B. Then the amount of current induced in the imaginary ship frame will be equal to k B cos θ. Let us represent this as O S. If O R represents the apparent directions of signals, then a rotating frame will have to be placed at right angles M O N to this direction. The amount of current induced in the frame in this position will be zero, and will be equal to the algebraic sum of the

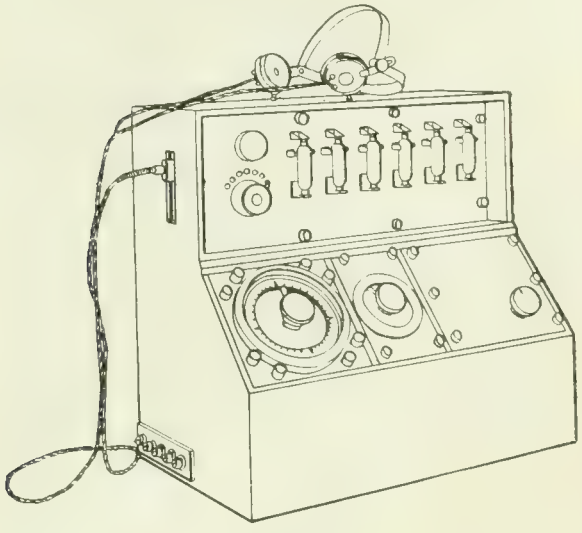

FIG. 33.

current induced in the frame by the ship and that by the signal. That is M O=N O.

$$\begin{aligned} \text{M O}=\text{O S}\cos(\text{S O M}) &= k\,\text{B}\cos\theta\cos\{90-(\theta-\phi)\} \\ &= k\,\text{B}\cos\theta\sin(\theta-\phi) \end{aligned}$$

$$\begin{aligned} \text{N O}=\text{O K}\cos(\text{K O N}) &= \text{B}\cos(90-\phi) \\ &= \text{B}\sin\phi \end{aligned}$$

$$k\,\text{B}\cos\theta\sin(\theta-\phi)=\text{B}\sin\phi$$

If ϕ can be considered small with regard to θ, then we have

$$k\,\text{B}\cos\theta\sin\theta=\text{B}\,\phi$$
$$k\sin 2\theta=\phi$$

That is the error is proportional to sin 2 θ, which is approximately the error shown by the curve.

CONCLUSION.

I am afraid that if I attempted to mention the names of all those who have assisted me during the last five years either directly or by advice, I should take up a large portion of this paper. However, I can never forget the valuable help and support of Colonel Blandy, R.E., of Captain Slee, R.N., of all the Wireless and Intelligence men at the War Office, the Admiralty, the Signal School, the Grand Fleet and Queenstown. Also to my own assistants at different times during this period, Lieut.-Commander W. T. Ditcham, Captain Tremellen, Lieuts. G. M. Wright, W. J. Picken, J. G. Robb, G. C. Meikle, A. W. Hall and Mr. F. P. Swann.

APPENDIX 1.

The action of a wave on two spaced aerials can be written down when subtracted as :—

$$\sin p\,(t-\tfrac{1}{2}\,\text{T}\cos\theta)-\sin p\,(t+\tfrac{1}{2}\,\text{T}\cos\theta)$$

where T is the time taken for a wave to travel from one aerial to another, and θ is the angle between the direction of the wave and the plane of the two aerials.

This is proportional to cos $p\,t$ sin $(\frac{1}{2}\,p\,\text{T}\cos\theta)$

$$p\,\text{T}/2=2\pi\,n\,\text{T}/2=\pi\,\text{T}/\text{T}_o$$

where T_o is the time taken for a wave to travel one complete wave-length.

Sin $[\pi\,(\text{T}/\text{T}_o)\cos\theta]$ is equal to $(\pi\,\text{T}/\text{T}_o)\cos\theta$, if T is small compared with T_o, so that the expression A cos $p\,t$ cos θ represents for a small frame the electromotive force induced. The phase of the electromotive force is 90° away from the phase of the electromotive force induced in one aerial.

With a frame, the effect of the term sin $[(\pi\,\text{T}/\text{T}_o)\cos\theta]$ being different from $(\pi\,\text{T}/\text{T}_o)\cos\theta$ if the frame is large, makes no difference to our reading of the minimum of signals, but with the Bellini-Tosi the effect is to cause an octantal error.

Thus if θ is the true direction with regard to the phase of one of the aerials and ϕ the error, then

$$\tan(\theta+\phi)=\frac{\sin[(\pi\,\text{T}/\text{T}_o)\sin\theta]}{\sin[(\pi\,\text{T}/\text{T}_o)\cos\theta]}$$

ϕ is zero for θ=0, 45°, 90°, 135°, and 180°, rising to a maximum between each of these pairs of readings. This error is actually extremely small with valves of T/T_o up to 1/10.

APPENDIX 2.

In the elementary consideration of the valve as an amplifier, it simplifies the initial considerations to neglect reaction effects. Grid current can also be neglected. If the characteristics of a three-electrode valve are drawn out (Fig. 34), plotting anode current against anode volts, a set of characteristics is obtained, each taken at constant grid volts.

If the valve is inserted into a circuit, whatever happens in the rest of the circuit the valve must obey the law given by this set of characteristics. For very small amplitude changes, this surface can be represented by the equation :—

$$i=u/r_1+v/r_2+\text{K}$$

where i=anode current,
u=grid volts,
v=anode volts.

K may be eliminated by a suitable shift of the zero of the axes to O, and the equation then becomes

$$i = u/r_1 + v/r_2 .$$

Let an element of the resistance amplifier be taken (Fig. 35). Then in the anode circuit there is a battery of voltage V_0, and also a resistance R. The voltage across the resistance rod equals $(V_0 - v)$, therefore

$$i = (V_0 - v)/R$$

This represents a straight line, which is shown in Fig. 34. If again the zero position is changed to O (Fig. 35), then $i = -v/R$ is the equation of this line.

For any change of grid volts, it is now possible to read off the change of anode current and anode volts.

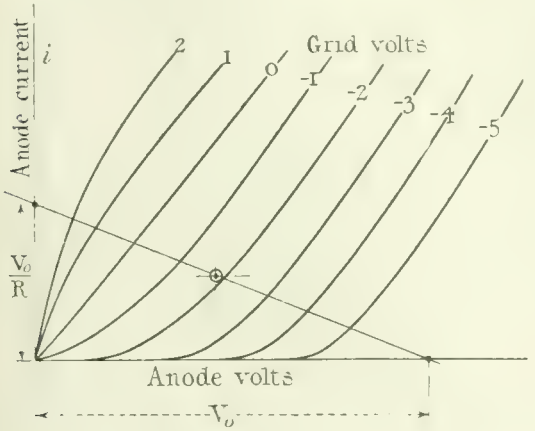

FIG. 34.

Instead of a graphical determination the solution may be obtained as follows :—

$$i = -\frac{v}{R}; \quad i = \frac{u}{r_1} + \frac{v}{r_2}$$

either i or v may be eliminated.

Eliminating i

$$-\frac{v}{R} = \frac{u}{r_1} + \frac{v}{r_2}$$

$$\therefore \frac{u}{r_1} + v\left(\frac{1}{r_2} + \frac{1}{R}\right) = 0$$

$$\frac{u}{r_1} = -v\left(\frac{1}{r_2} + \frac{1}{R}\right) \quad \text{or} \quad \frac{u}{v} = -r_1\left(\frac{1}{r_2} + \frac{1}{R}\right)$$

This expression has its smallest value when $R = \infty$. When $R = \infty$, v/u is usually called the voltage amplification factor of the valve and is equal to r_2/r_1.

If R becomes negative, as in the use of a dynatron, and $R = -r_2$, then v/u becomes infinitely large.

In the case when the more complex general circuit is attached to the valve (see Fig. 36), if i_1, i_2, and i_3 are the three currents flowing in L, C, and R respectively, and i is the sum of these, then

$$i = i_1 + i_2 + i_3 = \frac{u}{r_1} + \frac{v}{r_2}$$

Let $v = A \sin pt$. i_1 is given by the solution of

$$L\frac{di_1}{dt} + R\,i_1 = A \sin pt$$

that is $$i_1 = -A\left[\frac{r_3 \sin pt - pL\cos pt}{r_3^2 + p^2L^2}\right]$$

The minus sign appears for the same reason as in the simpler resistance case. A rise of volts across R is

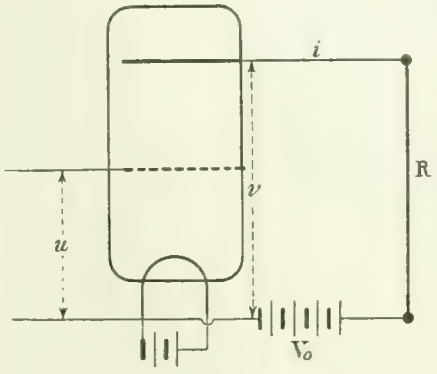

FIG. 35.

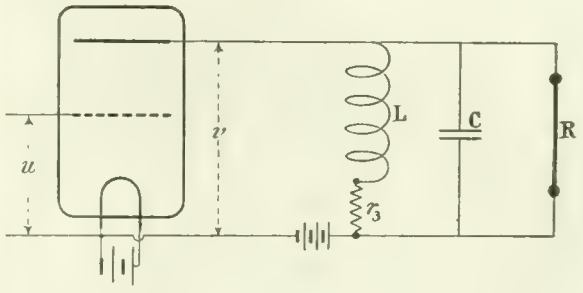

FIG. 36.

accompanied by a drop across anything else in series with it.

Also $$i_2 = -C\frac{dv}{dt} = -CAp\cos pt$$

and $$i_3 = -\frac{v}{R} = -\frac{A\sin pt}{R}$$

then $$-i = -\frac{u}{r_1} - \frac{A\sin pt}{r_2}$$

$$= \frac{A\sin pt}{R} + CAp\cos pt + \frac{Ar_3\sin pt}{r_3^2 - p^2L^2} - \frac{ApL\cos pt}{r_3^2 - p^2L^2}$$

or $$-\frac{u}{r_1}$$

$$= A\left[\frac{1}{R} + \frac{1}{r_2} + \frac{r_3}{r_3^2 + p^2L^2}\right]\sin pt + A\left[Cp - \frac{pL}{r_3^2 + p^2L^2}\right]\cos pt$$

Calling the amplitude of $u = A'$

$$A' = Ar_1\sqrt{\left[\frac{1}{R} + \frac{1}{r_2} + \frac{r_3}{r_3^2 + p^2L^2}\right]^2 + \left[Cp - \frac{pL}{r_3^2 + p^2L^2}\right]^2}$$

This general formula giving A'/A will serve to indicate the amplification curves of three cases of the

valve amplifier, the figures, however, not referring to any actual case.

(1) Let L = 0; C = 10^{-11}; R = ∞ ; r_2 = 20,000 ; r_3 = 20,000 ; r_1 = 3,300.

This is the case of a resistance amplifier with capacity, due to valves and leads, shunting the resistance.

Curve 1 (Fig. 37) shows the variation of A′/A with wave-length.

(2) Let L = 1/220; C = 10^{-11}; R = ∞ ; r_2 = 20,000; r_3 = 0; r_1 = 3,300.

This is the case of an inductance with capacity and no resistance and is shown in Curve 2 (Fig. 37).

(3) Let L = 1/220; C = 10^{-11}; R = ∞ ; r_2 = 20,000; r_3 = 20,000 ; r_1 = 3,300.

This is the case of an inductance wound with resistance wire with capacity, and is shown in Curve 3 (Fig. 37).

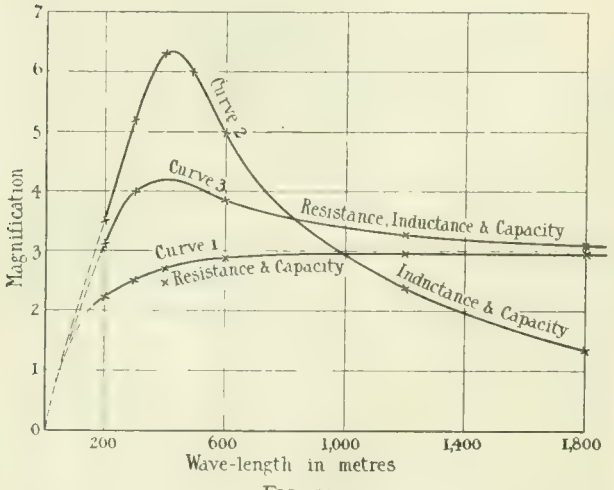

FIG. 37.

Where it is required, the amplification can be kept up on the shorter wave-lengths in the manner shown by Curve 3.

The curves for several valves in cascade can be calculated by taking the new amplitudes and applying the formula again ; or merely by squaring, cubing, etc., the first curves obtained.

A fair agreement can be obtained between experiment and this simple theory, if during the experiments reaction is eliminated. In general, for spark work, it can be assumed that full reaction multiplies voltage magnification by 7 or 8, if a practical adjustment is all that is permitted.

APPENDIX 3.

One of the great difficulties during the war was the jamming experienced in busy times, and the problem of jamming-prevention during direction-finding work is not at all the same as jamming-prevention during reception.

If, during the action of taking a swing reading, a strong station is sending, it is very difficult to obtain the necessary balance of signal strength, as the jammer, being in another direction, exhibits unequal strengths at the two swing positions.

A little was done with note-tuning by means of a valve reaction circuit tuned to the Telefunken notes.

However, in an attempt to develop one method, another was developed which turned out of great use in the allied work of interception, and it will probably be of use to describe it here.

In about 1910, Mr. C. S. Franklin and the author devised the two now well-known ways of limiting strong signals.

(1) The Fleming valve current saturation method;
(2) The Fleming valve or crystal, balance method.

Both these methods depended on the fact that signals of equal strength do not necessarily have the same maximum voltages or currents for the same R.M.S. values of current.

For instance, in an old-fashioned spark the maximum voltage or maximum current is quite large compared with the R.M.S. volts or R.M.S. current, whereas in continuous waves the maximum voltage and current are only 1·4 times the R.M.S. value, and approaching this in the case of a Telefunken spark.

Taking the case of the Fleming valve running with

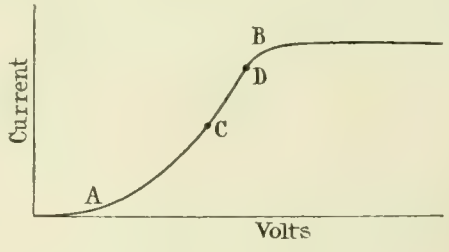

FIG. 38.

a dull filament, the maximum R.M.S. current that can pass can be limited to the strength of the Telefunken spark. Now any slow old-fashioned or low-note disc spark will obviously be proportionally weakened at this value of filament current if its R.M.S. value of current is the same as this Telefunken spark. (As a matter of fact the general reduction of signals was more than one could stand for, until high-frequency amplification was introduced.)

In the case of balanced valves or crystals, a voltage-limiting scheme is used, but in this method, which with crystals was difficult to work but very good when obtained, a new effect could be produced, which effect was the elimination of strong signals from weak ones, both strong and weak signals being on the same wave-length.

After the first high-frequency cascade amplifiers were produced, Lieut.-Commander W. T. Ditcham, who was in charge of one of the largest group of stations, undertook to develop a simple and more effective balance or saturation device.

The result was so simple to adjust, and so effective, that we introduced it for all interception work, and I

believe a good many ship working stations used it with great effect.

Ditcham's arrangement consisted in dulling down a valve, and instead of working at the rectifying point, having a potentiometer which controlled the characteristic from end to end.

He then found that with a particular filament brilliancy, at one point on the potentiometer one station would vanish, and at another point a different station would vanish.

An extremely fine potentiometer adjustment was

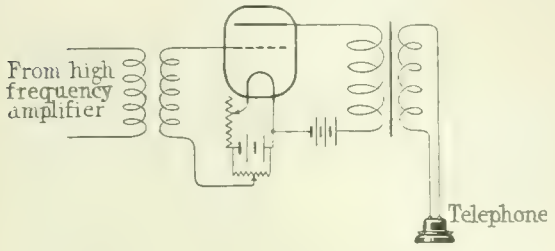

FIG. 39.

required to get the best effects, as the zero point of two stations will be separated by as small as 1/100th of a volt charge on the potentiometer.

The success of the device depended on plenty of high-frequency magnification before rectification, as these special points on the rectifying valve were rather inefficient rectifiers.

I can perhaps explain how this effect occurs.

Suppose a weak Telefunken station is being received and on the same wave-length a strong station with preferably a lower musical or unmusical note is also being received. The valve is dulled down to a value which prevents the full value of the loud station current passing through the valve.

If we draw the characteristic of such a valve, let A and B be the two maximum rectifying points. Now as the strong station voltage amplitude is at least from A to B horizontally, it can easily be seen that an approximate zero of rectification will be obtained at C the middle of the curve, but as in nearly all valves the curvature of the rectifying point is not the same at A and B—the zero rectifying point for the weak signal will not be at C but at some point D, the point of inflexion on the curve. The result is that at C the strong station vanishes but the weak station is still heard.

Those who have a high-frequency amplifier of any type, preferably with inter-valve transformers wound with copper wire, and not having resistance rods and grid leaks, can try this, as almost any three- or two-electrode valve shows the effect.

It is proposed to introduce a modification of this scheme, even simpler than the above, into all ship receivers for spark work. The amplifier to be provided is sufficiently sensitive, without the balance scheme, that ranges are increased very greatly over those with crystals only, and with the balance scheme the sensitiveness is about that of a crystal. In compensation, however, by the adjustment of one handle one is able to eliminate jamming.

This scheme enabled us to use note tuning much more effectively, for the signal strength was then not sufficient to set our note reaction circuit oscillating in its own period for a relatively long time, as is the case with strong signals.

We have noticed that the scheme is extremely effective on short waves for wireless telephony, for in such a case one has the limiting difference between sparks and continuous oscillations, and sparks can be almost all eliminated.

Unfortunately, I cannot say that its use is of equally great value for long-wave working, for with long waves there is not such a big difference between the maximum and R.M.S. value of currents.

The above saturation balance method was occasionally of use in direction-finding work, but its use was not at all general as the tendency is to require a curve which, if anything, exaggerates the cosine diagram.

DISCUSSION.

Admiral of the Fleet Sir H. B. Jackson : The difficulties experienced in classifying errors in direction and the means of eliminating them and correcting the observed bearing are not the least interesting items in this paper. A remark on page 237 personally appeals to me. The author states that " The extent to which direction-finding was trusted by the authorities was really remarkable," and he instances a most important event in the history of the British Navy brought about by an observed motion of less than 1½ degrees in the daytime. I think I may say we trusted him and his methods because we soon found them to be reliable. The trouble and intelligence of his staff reduced the errors to a minimum, and where strategical movements were under consideration a few miles of error in the North Sea was of secondary importance. I think it may be of interest if I give a few particulars about the case quoted in his paper, as it is really known to very few. We have heard much about the use of direction-finding for minor tactical movements of all arms, but this is a case of a major strategical operation which brought about the historical meeting of the British and German Fleets at the Battle of Jutland on the 31st May, 1916. I was First Sea Lord at the time and so was responsible for the disposition of the Grand Fleet. I may incidentally mention that, in spite of other statements of which I have heard, its Commander-in-Chief (Lord Jellicoe) and I lived, so to speak, with the object of bringing off such a meeting. Our wireless direction-finding stations, under Captain Round, kept careful and very intelligent watch on the positions of German ships using wireless, and on the 30th May, 1916, heard an unusual amount of wireless signals from one of the enemy ships which they located at Wilhelmshaven. This was reported to me; the time was a critical and anxious one in the war and I had also some reasons for expecting that the German Fleet might put out to sea during the week. Our Fleet was

ready at short notice and had arranged, unless otherwise prevented, to put to sea on the following day for a sweep of the North Sea. But if the German Fleet got to sea first, the chance of a meeting in waters not unfavourable to us was remote; our object was to try to get to sea before or shortly after the Germans, and hitherto we had not succeeded in doing so. Later on in the afternoon, it was reported to me that the German ship conducting the wireless had changed her position a few miles to the northward. Evidently she and her consorts had left the basins at Wilhelmshaven and had taken up a position in the Jade River ready to put to sea. This movement decided me to send our Grand Fleet to sea, and move towards the German Bight at once and try to meet the German Fleet and bring it to action. This they did with their usual promptitude, and the result was the famous battle of Jutland, and it was indirectly brought about by the careful and accurate work of Captain Round and his staff, for which I hope they will now accept my belated thanks and appreciation. Their work is not ended. Direction-finding has come to stay for more general use in peace. Errors are being eliminated and there should be a great future before it, especially on the lines indicated in the Press to-day by the Admiralty for assisting navigation at sea as well as in the air.

Squadron-Leader J. Erskine-Murray: There is one little bit of ancient history that I should like to mention, namely, that those two single aerials were first used, as far as I know, at the Haven early in 1899 when I was assisting Mr. Marconi, probably before Mr. S. G. Brown tried it. I erected them in order to minimize interference. It might seem rather early in the day to do so, as there were only two stations in the world at the time, but it was quite obvious that interference was going to be a trouble, so I started trying to get out a directional transmission method and used two aerials with a wire connecting the bottoms and a spark-gap in the middle. Unfortunately it did not appeal to those in charge of the affairs of the Company at the time, and I was criticized severely for wasting the batteries. That was the end of the attempt. There is one point which is strongly emphasized in the paper itself, namely, the difficulty of the conditions which surround the system known as the Bellini-Tosi. That can be seen in the paragraph on "Practical question of readings," and indeed throughout the paper. The author mentions that for accuracy the radiogoniometer has to be placed in the right orientation. This is natural because it is part of the aerial itself. It was reasons such as these that made those of us who were in the Royal Naval Air Service at the time try to find some new method which would be more suitable for use in aircraft. In the paper the author refers a good deal to "obvious ways" and "simple steps." They may have been obvious ways and simple steps to him, but in many cases these things are not quite obvious until after one has done them. For instance, he speaks of the case of the crossed coils, which are rotated to get equal signals in the R.A.F. system, as an obvious and simple step from the Bellini-Tosi. It does not seem so to me, and perhaps he will let us know when publication of such an arrangement was made. Switching over from one coil to another or reversing an auxiliary coil, as is done in the R.A.F. system, in order to obtain a strong signal with which to work, and the comparison of two loud sounds, does not seem to have been implied in the Bellini-Tosi patents at all, or in any description of working them. The Air Force scheme is more accurate, I think. It is a little slower unless one uses an automatic switch, and then the time is practically the same. With the actual R.A.F. system we have attained, as the result of a great many observations, to an accuracy of $1\frac{3}{4}$ degrees in the air, which means a great deal more on the ground; in fact, we have at present got sets which we can guarantee to $\frac{1}{4}$ degree on the ground. I do not say that with this set one could take an almost instantaneous bearing at a ground station, such as is required in the locating of Zeppelins and submarines. That, no doubt, is as well done as it could be by the system with which the author is working. I note, however, that the author says that he may possibly introduce switching in the future in aircraft. Most of the errors discussed in the paper are, as the author points out, peculiar to the Bellini-Tosi method and do not apply, or apply only in a very limited degree, to the small crossed coils. With regard to errors due to non-vertical wave fronts, waves from an aeroplane, for instance, I think it is hardly fair to ascribe the whole credit of their explanation to Eckersley. Hack's paper, which was published in the *Annalen der Physik* in 1908 and which was abstracted in both of the later editions of Zenneck's book, and in fact in my own book too, shows the rotating field in a vertical plane in the case of various types of earth, the variation being due to water below the soil at different depths. His diagrams show that the wave begins with a voltage in a horizontal direction which rotates as a vector, but every wave practically produces the same form and therefore an aerial, to obtain a maximum effect, must be parallel to the axis of the curve. Tremellen's results really interest me more than anything in the paper from the purely scientific point of view, particularly the result in which he describes how different apparent directions are obtained from two stations transmitting from practically one position if the aerials at the two stations are of different types. Obviously both sending aerials must be more or less directive, hence I think we can explain the result by suggesting that it is caused by the mutual repulsion of the lines of force as they go out. If a beam is sent out in one direction there is repulsion between the lines of force in it, thus there is a tendency for them to spread and therefore for the transmission of energy to be in curved paths except in the maximum directions. This explains why two different directions are obtained from the two different sending stations. It would also explain why the directional effect of a transmitting aerial disappears to some extent at great distances. There is only one other point I want to mention: I think the author has not given quite enough credit to some of those who have done a great deal of the work mentioned in the paper. For instance, the work in connection with magneto noises on aeroplanes was done by Professor Townsend, of Oxford, while a lieutenant in the R.N.V.R. He initiated the braiding of cables, and the rest of the work was carried out by R.N.V.R. officers at Cranwell. I do not think the

author has done justice either to Professor Townsend or to the late Mr. Russell Clarke, whom he dismisses with a rather disparaging remark, based apparently on the performance of some apparatus which does not seem to be Russell Clarke's own apparatus. Then there are the R.N.A.S. officers who evolved the direction-finding system which made direction-finding practicable in aircraft, and lastly Professor Artom, whose invention is said to have been misunderstood because of the indefiniteness of his description. With regard to Professor Artom, I suggest that the indefiniteness possibly consisted in the fact that he used a lot of technical terms about polarized waves. These may have been rather confusing to those who were not accustomed to the terminology of light. There is one point I should like to see corrected in the paper, and that is the author's endorsement of the claim to the invention of the radiogoniometer by Bellini. I believe the author must have seen Mr. Bellini's disclaimer during the last three or four weeks in the advertising pages of the *Electrician*, and also the statement by Professor Artom's agent in the issue of the 9th January, quoting the decision of the Italian Courts—in which the invention of both the radiogoniometer and the dirigible triangular aerial are ascribed to Artom. These criticisms of the paper do not, however, affect in any way my admiration for the remarkable work actually done by the author himself and the thorough and interesting manner in which he has described it.

Professor G. W. O. Howe: Our conception of the electromagnetic waves travelling in a regular manner over the surface of the earth, is evidently very far from the truth, and it is very disconcerting and disappointing to learn that direction-finding must in many cases be treated with more than suspicion. In view of angular errors of 30 degrees, and in one case I believe of 90 degrees, mentioned in the paper, one is rather surprised to hear what Admiral Jackson has just told us—that the Admiralty began to move the Fleet when a German ship appeared to have moved a few miles up the river. Evidently they had great faith in a very small angular movement in that case. It often happens that scientific research undertaken with one definite object leads to results of vast importance in other and unexpected directions, and it appears to me that these experiments that were undertaken, primarily with the object of direction-finding, are likely to prove very useful in throwing light on the transmission of electromagnetic waves around the earth. The paper teems with suggestive remarks in this connection. One of the most bewildering statements in the paper is that the direction as found from the marking wave of a continuous-wave station may differ by as much as 30 degrees from the direction as found from its spacing wave. It seems very difficult to think of a possible explanation. It is quite apparent, however, that the signals that one receives from a distant station have not travelled in the usually accepted regular way over the surface of the earth to the station, but that they have been transmitted into the upper atmosphere and then been reflected from some upper conducting layer or refracted in passing through ionized strata. These upper layers seem to be anything but plane or spherical; they appear to be very irregular, with the result that reflection takes place at very queer angles; in fact, it is something like billiards in three dimensions. Like Dr. Erskine-Murray, I was a little surprised at the way in which the author dismisses the Robinson system of switching over two coils in series that was developed in the Royal Air Force. I have had no actual experience with it, but I was under the impression that it represented a great advance in direction-finding, and I look forward with interest to hearing what those officers have to say who have been employed in the development of that system. In connection with Fig. 23, I should be glad if the author would say what the probable accuracy of the individual readings is. Within a few minutes the readings varied from 140 degrees to 147½ degrees. Is this variation quite outside the range of instrumental errors? If those readings actually represent the direction of the received signal at the station, it shows some surprisingly rapid movement in, I presume, some ionized upper layer, which is the only thing which can move about and cause such changes. Since the meeting I have learnt that, at Washington, the apparent bearing of the New Brunswick Station 175 miles away sometimes changes at sunset and sunrise by more than 60 degrees in a quarter of an hour. In a paper read two or three weeks ago before the French Société des Electriciens, I notice that M. Brillouin mentioned that at a French direction-finding station at Briançon they always located the Spanish land stations as being somewhere in the Mediterranean. The Pyrenees in between cut off the direct transmission readings, and the waves received were the ones that had gone out into the Mediterranean and up the Rhone Valley. Direction-finding over a stretch of land which includes mountains is obviously impossible under these conditions. In the third paragraph of the first column on page 224, the author states: "For consideration, an electrical wave can be divided artificially into two components, the electrical and the magnetic components." I see from a statement a little lower down on the page that he has no mistaken ideas about the point, but I think the statement is a little dangerous. There are so many people who calculate the effect on the aerial of the magnetic component and then of the electric component, and add the two together. At the top of page 226 the author refers to a leaky dielectric or condenser; I think it would be much better if the word "imperfect" were used instead of "leaky."

Lt.-Col. S. C. Wace: There is a point on page 238 which I think might be subject to a little explanation, where the author states that, because an Austrian submarine comes up, makes signals, gets her position and then goes down again, it is an argument against linking up position-finding stations by wireless. As a matter of fact, what happened was that the positions were announced in plain language. There were reasons, which I need not go into here, which led to that announcement. There are of course many arguments for using wires in preference to wireless for linking-up stations, but we could not help using wireless in the Mediterranean.

Mr. J. E. Taylor: I am not very clear as to how

far the present system of directional wireless with frame aerials is an improvement on the original Bellini-Tosi system, in which unclosed aerials are used. My small experience has been limited to the original Bellini-Tosi system with unclosed aerials, and I found in that case that it was very difficult to prevent some sort of a coupling between the two sets of aerials, which I rather assume would give rise to considerable trouble in practice. Those are two closely tuned circuits, so that a very slight amount of coupling between the aerials would be sufficient to upset the direction-finding. Presumably with the frame aerial that difficulty does not exist to the same extent. The only other point to which I want to refer is the question of the reflection from the supposed ionized layer in the atmosphere. I am not quite prepared to admit that that is a proved condition yet, but if reflections are caused from irregularities in this ionized layer which give rise to anomalies in the direction-finders, surely the same sort of irregularities or anomalies in direction-finding would result from reflections which undoubtedly do take place from excrescences on the surface of the ground. They should act in a similar manner to excrescences on this ionized layer, and these should usually be in evidence in the daytime as well as at night. I do not know whether the reflections from the supposed ionized layer are only evident at night. It is a point of considerable theoretical interest, and if any further information can be given I should be very glad to hear it.

Major C. E. Prince: As a more or less impartial observer perhaps I should like to say a few words on the point Dr. Erskine-Murray raised as to why the R.N.A.S. system of switching-over has not been given the attention it deserves. It came before me when I was at Biggin Hill, and I had to form an opinion on it. It seems to me an excellent system in its way, and it has a field of usefulness under certain conditions, but it has the inherent defect of four points of ambiguity. When it was introduced it was apparently thought, even by the inventors themselves, that they were actually finding directions on a maximum, but it was pointed out by Dr. Widdington and others that they were actually determining the direction by the ordinary minimum method of a coil at right angles to the arriving signal, but superimposing upon this a constant signal, since the change on the frame in the direction of the signal is so small within the small limits of a searching movement that we may call it a constant. Therefore it comes practically to this: a constant signal superimposed upon the change which is found by the ordinary minimum method. The whole problem resolves itself mainly into a psychological one of whether the operator finds it easier to compare two signals thus, or by swinging over the zero.

Mr. J. St. V. Pletts: We seem to have heard rather more of the defects of the direction-finder than of its merits, and I should like to draw attention to one paragraph which is a distinct triumph for it. The author says: "The German submarines were fitted with powerful spark stations working on 400 metres, and I very much doubt whether a signal was ever made by one without our stations recording the position." I think that is something to be proud of. The author referred to the part I took in the production of the maps which were used for plotting the results obtained from the direction-finders. I have pointed out elsewhere* that the gnomonic projection to which he refers is not the best for this purpose unless there are more than two stations from which the results have to be plotted. The gnomonic projection has three advantages. In the first place, all straight lines on the map represent great circles on the sphere; or in a single word, it is orthodromic. In the second place, it gives true directions from one point; or is azimuthal. And in the third place, as has been shown by Dr. Eccles,† it is possible to get true distances from it by a comparatively simple graphical method. I think the azimuthal property looks a good deal better than it really is, because, except for places in the vicinity of the tangential point, it is essential for accurate results to draw a protractor round each place; and if protractors have to be drawn it does not much matter if they vary considerably from equal divisions. Therefore, unless the ability to get distances from the chart is essential, the only property of the map which is really important for this purpose is its orthodromism; and that property is not solely confined to the gnomonic projection. Whenever a wireless map is required of a long thin strip of territory, the distortion at the ends becomes very considerable with the gnomonic projection, and I think it is much preferable if the scale of the map at right angles to the length is magnified so that the distortion is reduced. The author points out that if a light be placed at the centre of a transparent earth one gets on a screen the gnomonic projection; but, if that screen is replaced by a lens which converts the divergent beam of light into a parallel beam, we can get a magnification in one direction by placing our screen obliquely in the parallel ray of light. The map so obtained is of course neither gnomonic nor a projection, but it is orthodromic, and therefore it is quite as useful for direction-finding purposes when once it is provided with the proper protractors. In short, the gnomic projection is only a particular case of a large family of orthodromic maps, and it is orthodromism that we really want. I have often wondered how the word "gnomonic" came to be used in this particular sense, and although the explanation recently given me by a draughtsman, that it was somehow derived from the word "goniometric," may not be the right one, it is as good as any I know.

Captain C. T. Hughes: The development of the wireless direction-finder must have been hampered at times during the war by the fact that publicity would have been fatal to its chances of success. This was particularly the case when the organization for dealing with hostile artillery aeroplane wireless was being built up. The author refers to the work done by the rotating-frame direction-finders in dealing with hostile artillery machines. I am afraid the early work of these frames rather endangered our friendly relations with the Royal Flying Corps pilots. It was a little unnerving, too, in those days, to find enemy stations apparently starting up work in our own lines. These little difficulties did not help to create that atmosphere of perfect confidence in the wireless direction-finder so necessary to the

* *Wireless World*, vol. 7, p. 68.
† "The Year-Book of Wireless Telegraphy and Telephony," 1919, p. 906.

development of the work. However, time proved the value of the wireless bearings, and then opinions changed. I am glad to see that the author pays a high tribute to the operators. They did their work under great difficulties, and it is largely due to their keenness that the results were so excellent. The jamming during a Zeppelin raid, or later on in the war when the enemy trench wireless stations were numbered in hundreds, was something to try the finest operators. I see the author mentions sunset errors. Captain Tremellen's curve showing the variation in KAV's bearing at sunset is very interesting. It confirms to some extent a general impression I had about that time, that the bearings on a station situated to the east of the direction-finder tend to swing towards the south during the period of sunset error. I rather think the reverse was the case at sunrise. It would be interesting to know if this has been confirmed by other observers. I believe that during some recent tests in France, on transatlantic transmission from Annapolis, there was a marked tendency for the bearings to swing towards the north when sunrise occurred at the receiving station. The author says that the fact of a regular variation at sunset is not yet definitely established. For some three months past, working at Woolwich, we have noticed that bearings begin to go flat about 30 minutes before sunset. At sunset the minimum may sharpen up, but bearings will be wrong during a period of perhaps 10 minutes, and from that time until about an hour after sunset they often go flat again. Most of our observations have been taken on wave-lengths below 2,000 metres, and unfortunately we have not been able to keep regular watch, but I think it will be found that the sunset variation is present on almost any evening at this time of the year, though the magnitude of the change varies greatly at different stations. I know that the sunrise effect with KAV was repeated every morning at dawn in the spring of 1915. An important point we have noticed, but one which needs confirmation, is that the sunset variation appears to be less marked on a small frame than on a Bellini-Tosi aerial. We have kept simultaneous observations on a frame aerial 6 feet by 4 feet, and on a Bellini-Tosi untuned aerial on a 50 ft. mast 200 yards away from the frame. The wave-lengths received were between 600 and 2,000 metres, and we have frequently noticed that it was possible to get a sharp zero on the frame, while bearings taken on the goniometer were flat. I put this forward with some diffidence, as we have not been able to carry out continuous nightly observations, and the case is complicated by the fact that individual stations often vary rapidly during, say, a quarter of an hour, but it raises the question as to whether the large Bellini-Tosi aerial may be more subject to night effect than the small frame. I should be very glad to hear the author's views on the point. With regard to variation on Horsea's bearing, I have used the harmonics of Horsea quite a lot lately for check bearings at night, but have never noticed much variation in its bearing on tuning to the different harmonics—at any rate, not more than two or three degrees. What is very noticeable, however, is that the minimum on some of the harmonics is flatter than on the fundamental. The author will remember the German control station DK, which worked on a number of waves between 600 and 2,000 metres. I think its bearing did not vary more than about 2 or 3 degrees over this range of wave-lengths, unless there was a bad night effect on. I am inclined to think, from some occasional bearings that I have taken lately, that the night effect may be just as bad on short waves as on long waves when we deal with distant stations. I can confirm the author's observations as to the effect of wooded country. Some of the worst night bearings we ever had on short-range stations were taken on one of our stations working in the French lines in densely wooded country, though the direction-finder had half a mile of clear ground round it. Some recent experiments by the French Naval authorities support the author's experience with direction-finders placed on a hill. They tend to show that the variation in bearings set up by the formation of the hill is very marked in the case of a small frame aerial and is apparently a function of the wave-length. The position of the frame on the hill seems to be very important, a movement of 20 yards or so being sufficient to cause a large change in the refraction. The author suggests that the mass of a rotating frame will always make it difficult to use for very rapid work. I agree that the Bellini-Tosi goniometer is the most convenient instrument for snatching a quick bearing, but the development of the multi-valve amplifier has made the production of very light, small frames a practicable proposition. A well-designed frame 2 ft. square with the moving parts mounted in ball races, can be handled as rapidly as working operations are likely to require, and such a frame, with a 10-valve amplifier, has an effective range on ship stations of 250 miles. In point of accuracy it is, I think, inferior to the Bellini-Tosi system to the extent of a degree or so in observed bearings, but we have used frames 2 ft. square as standard equipment for some time, and have had no difficulties on the score of rapid manipulation. The introduction of the aperiodic Bellini-Tosi set marked a great step forward in point of ease of handling, but it still takes almost as long to lay out the aerials and erect the mast as in the case of the old tuned set. In my opinion, the choice of systems depends largely on what the station is wanted for. If a direction-finder is required to be moved rapidly from place to place, as in military work, then I think the frame is the better of the two. The great drawback to the direction-finder sets during the war was that they were not mobile, and there were many occasions when we would have been prepared to sacrifice extreme accuracy in order to get going with some sort of direction-finder capable of being erected anywhere and set working in a few minutes.

Lt.-Commander W. T. Ditcham: Having been connected with the working of the direction-finding stations of the Admiralty from their commencement, I had the fullest opportunity of observing the results obtained under all conditions for several years, and I know very well the difficulties that were encountered and had to be overcome, but the final result was such that, in my opinion, the wireless direction-finder was one of the great technical successes of the war. There is only one point in the paper on which I should like to take issue.

The author states that continuous-wave signals at night have the advantage over spark signals for direction-finding purposes in that they do not suffer from a change of note on the two sides of the minimum position. I do not think that statement is universally correct. I have distinct recollections of the despairing looks on the operators' faces caused by efforts to equalize the strength of two quite differently pitched notes when swinging the search coil through zero, and these unaccommodating signals emanated from certain arc transmitters at night time, ranging in wave-length from about 1,800 to 3,000 metres. My own experience has been that night effects of every kind are more pronounced with continuous than with damped wave signals.

Captain J. Robinson: This paper constitutes perhaps the most complete account of directional wireless that has so far been published. The author does not, however, do justice to the R.A.F. system, which consists of the use of two coils at right angles, one being placed on its maximum, and the other, with a reversing switch, on its minimum. When the coils are set accurately, the reversal of the minimum coil produces no change in intensity of signals. The author states that this system is really equivalent to the case of two coils with a change-over switch from one to the other. This is not the case, and the distinctions are most easily seen by reference to aircraft working, as the R.A.F. system was developed specially for this purpose. The first problem in applying directional wireless to aircraft was to enable an aeroplane to head towards a wireless station. This was very difficult by a single minimum coil athwartships, because the region of the minimum on an aeroplane is widened by external noises and magneto disturbances. The R.A.F. system enables one to use a coil as a maximum coil, i.e. in the fore and aft line, and accurately to determine this maximum by means of the minimum coil. This is quite distinct from the case referred to by the author where two coils are placed at equal angles from the maximum of each. Another point in which the system differs from the two aerials mentioned in the paper, is that the sensitiveness of the system is under control by altering the ratio of the sizes of the two aerials. There can be no question in the R.A.F. system as to whether one is on a maximum or a minimum of the main coil, since one commences by determining roughly the maximum of the main coil, any subsequent movement from this being small. An optical analogy of the difference between the minimum system of direction-finding and the R.A.F. system has been suggested. The minimum system can be compared with the use of a simple Nicol prism, whilst the R.A.F. system can be compared with the half-shade polarimeter. With regard to night variations, I have never observed errors as large as 30 degrees with small frame coils. Errors certainly do exist, but it is still doubtful as to whether all instrumental errors have been overcome. It is possible that the size of the aerials may have something to do with the amount of recorded variations. Again with regard to continuous-wave variations, my experience has been that unless great care is taken, large errors are obtained which are not variations of bearings. Some information that should be carefully studied in connection with continuous-wave direction-finding is contained in a paper by Armstrong* on the amplification of heterodyne signals. He shows that the amplification depends very considerably on the relative strengths of the incoming waves and the heterodyne oscillation. In the case of the fixed aerials using a radiogoniometer, if a self-heterodyne is used the aerials will absorb energy from the heterodyne and, unless extreme care is taken, the amount of energy absorbed will depend on the position of the moving coil and the radiogoniometer. Thus the amplifying power of the heterodyne will vary with the position of the moving coil. The reference in the paper to the radiophares is very interesting as showing that night variations are also observed with such a system. However, for purposes of navigation such a system has great advantages over the system where each aircraft or ship has its own direction-finding gear. One of the chief reasons for this is that the taking of bearings will be very much simplified. Again, on any occasion where night variations are bad, check stations can be made use of to discover this and so send out a warning.

Mr. B. S. Gossling: The salient point about the research of which this paper is a record is that whether the work was being carried on in the field in France, on the East coast of England, in the lamp works engaged in the development of the valves, in the author's own laboratory, or on the battleships of the Grand Fleet, the author was always there. That appears to be one way of keeping a true perspective in a research covering a very wide field—that those who are engaged in it should themselves see and hear and experience with their own senses the various phenomena with which the research is concerned. This is necessary in order that the natural tendency to elaboration of detail may be kept within bounds, the point of concentration at any time being determined, not by ease or interest but by intrinsic importance.

(*Communicated*) The theory of the valve attachment which really made direction-finding practicable is included in the paper incidentally, after the "Heaviside layer" and the psychology of the operator, and remarks on this subject are perhaps barely relevant to the paper as a whole. Still the following observation on the behaviour of the detecting valve will probably be confirmed by anyone investigating the effects described in Appendix 3, and is not consistent with the explanations put forward. I have observed that the "balance action" can occur when the filament is far too hot for the signals used to produce any saturation of space-currents. What happened was that as the oscillatory electromotive force applied at the high-frequency end of the apparatus was steadily increased, the strength of the rectified signals heard in the telephone increased at first, attained a maximum, decreased to a minimum, and then increased rapidly. The signals at their strongest were not loud, and characteristics taken at the time showed that 5 or 10 volts of positive potential applied to the grid produced no approach to saturation of the anode current. The balance action may be more effective with a dull filament, but is not absent with a brighter one.

* *Proceedings of the Institute of Radio Engineers*, July 1917.

Mr. E. H. Shaughnessy: We had considerable experience in running direction-finding stations during the war. As a matter of fact, the Post Office Engineering Department ran four of them, which were equipped by the author. Shortly after their erection Mr. Hinton found that aperiodic working was possible and that he could get a range of 200 metres on each side of the sent waves to which the aerials were balanced. Later on we made an arrangement in which two sets of condensers were used; one set of condensers joined to a pair of aerials gave a range of from 600 to 1,000 metres, setting the aerials at about 800, and with a change-over switch we could substitute for this set of condensers another pair which were already adjusted correctly and thus obtain a range of from 1,000 to 1,400 metres. That arrangement gave facilities for quick search, and it was very remarkable how accurate the results were that were consistently and very rapidly obtained at these stations by expert operators. The operators after a very short period found the work quite easy and that it did not involve much strain. We carried out some experiments with regard to coupling between aerials, and we introduced between two aerials a coupling balancer—a couple of pairs of D-shaped inductances which we could turn round. We very carefully tested to see the effect of any coupling between the aerials and never found that the coupling between the aerials gave rise to an error of more than $\frac{1}{2}$ degree in the readings.

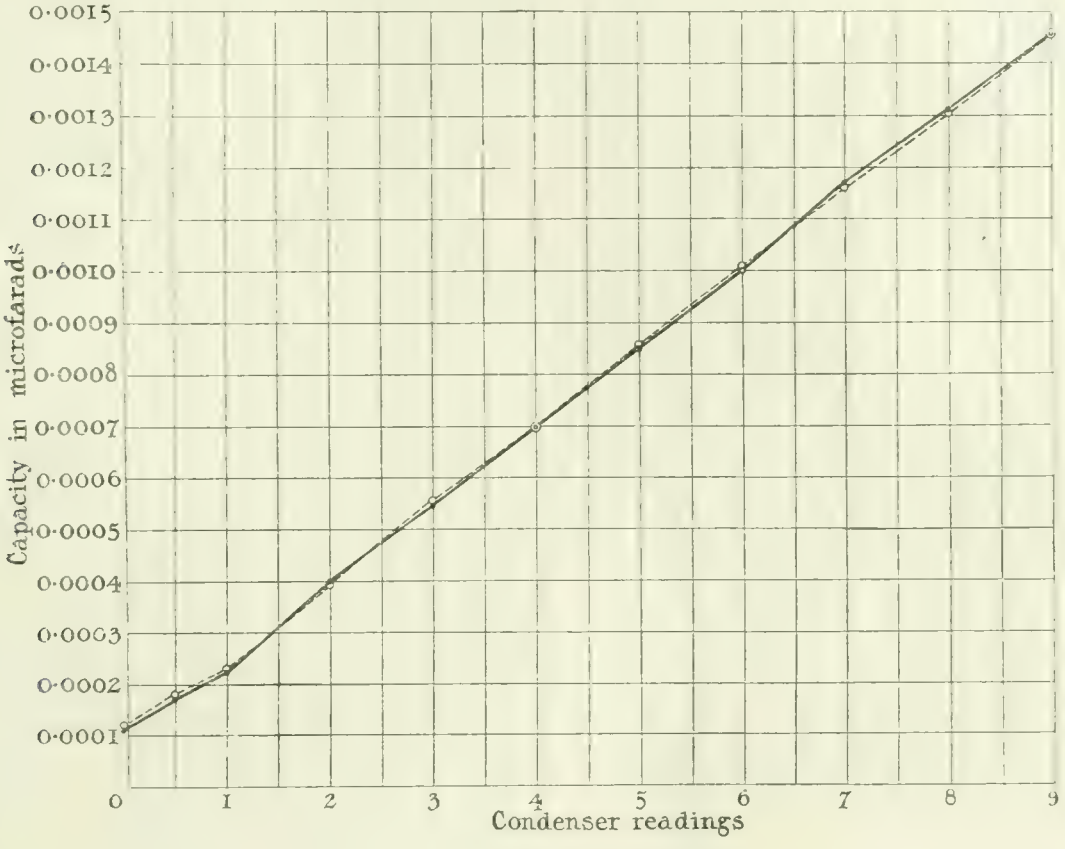

FIG. A.

There is one other point which I think has not been sufficiently brought out in the discussion, in connection with the early development of wireless direction-finding. I think that at one time direction-finding was very much neglected. I know the Post Office were going to buy Marconi directional wireless sets some time before the war, but were not satisfied that there was very much in it, or that they were very accurate or had a very long range. I think the real development was due to the fact that the author had worked very hard at producing a valve amplifier, and the introduction of this valve amplifier and its efficient application to incoming signals enabled him to investigate all the inaccuracies which had previously existed in the arrangement, to balance those inaccuracies out and produce a really efficient and accurate radiogoniometer set.

Dr. W. H. Eccles: The importance of direction-finding has of course lain in its application to the war, but, now that the war is over, those who are interested in the scientific aspects of the matter are very glad to obtain the observations recorded in this paper. Many of them confirm the French work done on the subject, which has been very extensive and thorough. For instance, Captain Brossier, who was at Salonika a long time, found that Paris gave readings correct within 1 degree in the daytime, but was often bad at night, and he extends the theory referred to by several speakers for explaining what happens. There is the usual verti-

cal component field that one expects from the vertical Hertzian oscillator, which arrives all right and seems to be the only component that does so by day. But at night an additional component arrives which is askew, that is leans partly forward or backward and partly sideways. If it only leans forward its effect is much the same as if it were vertical, but if it leans to one side or the other it produces the effect of adding another little frame at right angles to the original frame, with the consequence that the minimum is shifted. That is sufficient to explain the shifting of the minimum at night, but does not explain the fact that the minimum is not so sharp. To explain that, one has to admit that this new field not only has a horizontal component to the left or the right, but is also out of phase with the ordinary or day field. Then all the conditions are present that will satisfy the experimental observations. Brossie naturally suggests that this twisted field is due to reflection from the Heaviside layer, which appears to be, as one of the speakers has remarked, very lumpy or bulgy. Then the question arises why this leaning field is absent during the daytime. The reason has been suggested many times during the last 10 years, namely, that the sun ionizes the lower layers of the atmosphere in the daytime and so puts the upper layers out of action. The electric waves do not reach the upper layers in the daytime, but when the sun disappears and all the ions are re-combined the electrical fog and its absorbing and refracting qualities vanish and the upper layer can come into action: it becomes exposed to us and is not exposed till then.

Mr. H. M. Dowsett (*communicated*): The author has mentioned the difficulty experienced in obtaining

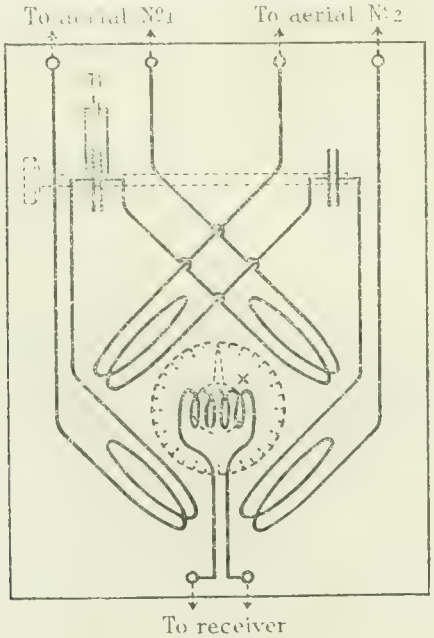

FIG. B.

condensers for the two aerials of the Bellini-Tosi system which would move together and give balance over the whole working range of wave-length. As described in the paper, he and his assistants avoided this difficulty by using two independently adjustable condensers. The attempts which were made, however, to produce good coupled condensers were not altogether unsuccessful, as is indicated by the calibration curves here shown (Fig. A) of one of several radiogoniometers constructed on this principle at the Marconi works in 1914. The closeness of agreement of the two condenser capacities over the whole of their range was obtained by much careful and repeated adjustment of plate area until they were satisfactory. The unscreened type of condenser employed in this case was made up of rectangular brass plates moving in grooves in an ebonite frame. It developed faults in service, and was superseded by a screened-disc air condenser, the two units being mounted on a common spindle. The plate area of this type was less easy to adjust, and a method of correction had to be introduced (1) for the difference of capacity between the units at zero on the calibration scale, and (2) for the difference of slope of the calibration curves which tended to cross each other. A fixed condenser was therefore added in parallel with one of them in order to separate the curves, and an adjustable condenser of the "billi" type—shown at B in Fig. B was added in parallel with the other so that the capacity of the two aerial systems could be brought to the same value throughout the whole wave-length range of the instrument. It is with satisfaction that one has noted the successful development of the aperiodic aerial system which does not require such adjustment, and therefore has considerably simplified the operation of direction-finding.

Major T. Vincent Smith (*communicated*): The application of direction-finding to aircraft is one of the most important uses to which this branch of wireless can be put, as the whole success of commercial aviation will depend very largely upon the use of wireless for navigation. The system used by the Royal Air Force was evolved by Captain Robinson, and I was much impressed by his experiments which I saw early in 1917. As the officer responsible for the wireless of the military side of the Royal Air Force during the greater part of the war, I did all I possibly could to encourage its development. The ear is remarkably sensitive in comparing the strength of two signals by means of a switch as in Captain Robinson's system, and the results obtained in practice prove not only the excellence of his system but its great importance for wireless navigation. I doubt whether it is possible in an aeroplane to obtain such accuracy in reading a zero position by means of swinging, though I confess to no experience in this method. For the purpose of training personnel in this work, the apparatus was set up in a light tender which cruised between Netheravon and Bournemouth, plotting its position by bearings taken from Stonehaven, Ipswich, Poldhu and Nantes. The results depended upon the skill of the operators, but were always accurate enough for aerial navigation except when the receiving station took bearings in the neighbourhood of barbed wire, overhead wires, or drain pipes. Even without these sources of error, Stonehaven near Aberdeen invariably appeared to be out of position. The signals from Poldhu were also deflected when flying over the Channel. I can testify to the usefulness of

the direction-finding done on the Western Front in locating enemy aeroplane activity. It was at first proposed to inform our fighting patrol of the whereabouts of enemy machines engaged in observing for their artillery, but owing to the disturbing effect of the necessary transmission the results obtained were not sufficiently good to justify the organization and training necessary to carry out the scheme. It was very useful, however, in indicating the grouping of enemy aeroplane activity and any change in the same, thereby enabling us to take the necessary counter measures. The author closes by thanking various people for their help, but it is quite certain that there is no single individual to whom the thanks of all branches of His Majesty's Forces are due in a greater measure than to the author. He was always ready with advice and suggestions, and placed himself unreservedly at everybody's disposal with a readiness which I am glad to take this opportunity of acknowledging, and to thank him not only for his paper but for all he did for the Royal Air Force.

Captain H. J. Round (*in reply*): The errors in direction-finding are of greater scientific interest than the practical questions involved, and it was because of this fact that they were accentuated in my paper. A wrong impression may therefore have been given as to the real accuracy of direction-finding. A station erected and checked by the position of a few known stations was accurate within one degree on daylight readings. Night-time readings of spark signals, if only the one station was available, were not very trustworthy. The operator, however, could nearly always judge, from the readings of check stations or from the presence of bad minima, the accuracy that could be attached to the readings. With a position-finding group of three or more stations, one station acted as a kind of censor. All bearings were sent to and were plotted at this station, and it was only when the bearings from all stations intersected at a point that they were allowed to pass. It was contended that if four directions intersected at a point or a close approximation to one, the readings were reliable. This censorship also tended to eliminate operators' errors both in reading the direction and on the land line. It was on account of these methods of using groups that night readings were made of value. Occasionally, for short intervals, readings from all stations made impossible intersections, and then no reports were made to those who acted on the readings. On continuous waves at night, bad intersections were the rule rather than the exception and, consequently, we could not make use of our readings to anything like the same extent as spark readings.

I must thank Sir Henry Jackson, the first of naval wireless experts, for his kind and encouraging remarks. It may seem almost heresy to say so, in the face of so many statements to the contrary, but evidence I have received during the last year indicates that, in wireless work at least, our General Staff were much more alive to the power of the expert than the German leaders. The fact that Sir Henry Jackson was a wireless expert as well as First Sea Lord had probably a great deal to do with this.

Referring to Dr. Erskine-Murray's remarks, I was not aware of his work at the Haven, but I have since found the record of it in his books and I must apologize for not mentioning it. I can quite believe the incident of the accumulators, as I remember getting into hot water myself on the same subject. If he will remember, the accumulators were charged from dry cells, and such uneconomical methods doubtless made those in charge over careful. In regard to Bellini-Tosi methods versus "switch key" methods, I am glad to note that Dr. Erskine-Murray classes the reversing coil of the R.A.F. with the crossed coils I pointed out in my paper. If he will refer to a patent specification of mine, No. 11,544, applied for in May 1909, he will find the following:

"The object of this invention is to provide improved apparatus for wireless telegraphy by means of which it may be possible to readily ascertain with great precision the bearing of a station from which the signals are emanating.

"It is well known that with certain aerials which will be hereinafter called directional aerials, such for instance as those described in Specification No. 14,788 of 1905, the received signals are, other things being equal, of maximum strength when the aerial is situated in the vertical plane passing through the corresponding station, and that the strength of the signals decreases at first gradually but afterwards more rapidly as the aerial moves out of that plane in either direction.

"According to this invention we employ at a receiving station two directional aerials set at an angle to one another, and we provide a switch or key which can be thrown rapidly backwards or forwards to connect the receiving apparatus to each of the two aerials alternately.

"With such an arrangement the signals received from the two positions of the switch will be of unequal strength unless the transmitting station lies in a certain direction and this direction, if the two aerials are similar, will bisect the angle between them. Provided this angle is sufficiently large the direction of equality may be determined with great precision since the strength of the signals will then change rapidly with the angle."

A further patent by C. E. Prince, No. 2456/1912, uses the same arrangement with two frames. In 1914 I actually had, at one of my stations in England, a crossed-coil radiogoniometer. When it was made I do not know, as I found it in our works. Tests were carried out with this instrument. I meant to say in my paper that I thought the "switch key" method might be used in navigation, but actually I did not have in mind direction-finders on aeroplanes. Regarding Eckersley's explanation of the night errors, I think that Dr. Erskine-Murray must have misunderstood either Hack, or my exposition of Eckersley. Hack deals with waves tilted forward, and rotating electrical fields in the plane of propagation. Neither of these effects will affect bearings. Eckersley's work, however, deals with waves in which the direction of propagation is at an angle to the earth, and in which the electrical force is parallel to the earth and perpendicular to the direction of propagation. Any rotating fields produced

are due to the interference of this wave with other similar waves, or with the usually considered ray parallel to the earth's surface. Before this I had suggested the production of rotating fields due to rays parallel to the earth's surface having different lengths of path. Such an effect would be produced by diffraction round a mountain which was in the direct line of propagation, or by reflection from an irregular Heaviside layer. This was, however, a different possible effect from Eckersley's, and the real point in Eckersley's work was to note that the trouble was due to the frames having top and bottom conductors which could be acted on and cause errors in the readings produced by the sides, or vertical conductors. I disagree entirely with Dr. Erskine-Murray when he states that the directional effect of a transmitting aerial dies away. There is no evidence that the cosine diagram from a transmitting frame is different at a distance from that fairly near by. The German radiophares distinctly showed that, in their daylight effects, the minima at least were just as sharp at a distance as near by. I am sorry that my paper has given a wrong impression of my regard for Mr. Russell Clarke's work, for no one could hold it in a higher estimation than myself. I merely recorded the fact that what for other purposes was a very useful piece of apparatus, was not adaptable for the purpose under consideration.

I think that in the first paragraph of my reply I have partly replied to Professor Howe, and in my answer to Dr. Erskine-Murray I think I have made my position clear with regard to the "switch key" method. With regard to Captain Tremellen's curve, these earlier readings were probably taken by determining the apparent minima of strong signals. There would be actually no zero on these KAV signals. Very soon after these curves were taken I found out that these errors were reduced by taking broad swing readings, say 20° on either side of the minima (a point by the way certainly in favour of the "switch key" device if the swinging had not been so easy to do). Consequently I think these original KAV curves would now exhibit only about one-half of the errors shown. I do not know the exact reason for the improvement shown by taking these broad swing readings. I found out the result about February 1915, and gave instructions to all stations after that to take broad swing readings at night. I do not think Professor Howe distinguishes sufficiently between day errors and night errors or variations. Although mountains do have some slight effect, say up to two or three degrees, and do undoubtedly produce bad minima, the effects are constant and can be calibrated for by using the positions of known stations. Direction-finding over land is quite all right during the day. Mr. Ditcham has recently brought to my notice the fact that at the station in Norfolk, marked on the map in Fig. 24, it was observed that certain German stations had a gradual drift from north to south during the day. Heligoland was the station that had the greatest drift. In the forenoon the observed direction on this station had a $\frac{1}{2}°$ error to the north, at noon the reading was correct, and in the afternoon the error was $\frac{1}{2}°$ to the south. Such observations, if noted only once or twice, would have been put down to instrument or reading errors, but no doubt is entertained by Mr. Ditcham as to the accuracy of these small differences, as the observations were continued over an extended period. It would appear that, on these occasions, a remnant of night variations extended over the daylight period.

In answer to Mr. J. E. Taylor, I think the original Bellini aerials were replaced by frames by Major C. E. Prince in 1912, and undoubtedly the latter are superior. This is due both to the effects he mentions, and to the difficulty of handling what I term "Vertical" with such an open system. One must not forget, however, that the two open aerials as in Fig. 3, the original direction-finder, have no spaced cross-connecting leads, like a frame, to be acted on by skewed waves. I believe that I have mentioned some daytime errors due to ground excrescences, but all these daytime effects arrive in the equatorial plane of the receiver, whereas Heaviside layer reflections arrive at an angle downwards. The constancy of daylight readings from an hour after sunrise to within an hour of sunset is rather against any skewed reflections from the Heaviside layer, but it is no proof against a reflection in which there is no "aeroplane" component. After hearing Mr. Pletts, and also having read some of his wonderful expositions of the possible forms of maps that can be made, I can only add one new one; I think it was due to Captain P. J. Edmunds. By a mathematical transformation, he made a map of the North Sea in which all lines on an ordinary map became points, and all points became lines. The result was that all our direction-finding stations were represented as lines with scales on them representing directions. A Zeppelin position appeared as a point on each of these direction-finding station lines. Then if the directions were all correct, these points lay on a straight line, and if some bearings were slightly out the best average line could be taken, this line representing the Zeppelin position.

With regard to Captain Hughes's remarks, I am not at all certain about this swinging to the north or to the south. I quite agree with the regularity of the bad minima round sunset, but what I really meant was that at a first glance the curve of KAV looked like one which could be used for bearing correction. Unfortunately this is not the case. During the war several others beside myself have attempted to detect a difference between night effects on a frame and on the Bellini-Tosi system. Unfortunately, we could never find any difference. I might remark, however, that two stations placed even a few hundred feet apart do seem on occasions to get very different readings at night. The direction of Horsea's spacing and marking signs were taken on very many occasions, and there is no possible doubt about the great difference of reading being the rule, but the position of the receiving stations and the intervening land will probably have a lot of influence. The station giving the biggest difference was the above-mentioned one in Norfolk. I quite agree with Captain Hughes about the use of frames in many cases. Unfortunately, the only time I advocated frames for direction-finding work in England, they were erected and then rejected on account of

clumsiness when taking a reading, but that was with 5 ft. frames and an amplifier which was not as good as we have at present.

Lieut.-Commander Ditcham has certainly brought to my notice a new effect and a very puzzling one. He stated that on certain occasions, at night, the heterodyne note varied as the radiogoniometer search-coil was rotated. It is so strange that I am rather apt to think it was due to some inequality in the aerials, such as bad insulation or actual contact with a stay wire, otherwise one would have to assume an atmospheric frequency changer, unless the effect was due to some local atmospheric or ground effect acting more on one aerial than on the other. At other stations I can find no record of such an effect.

Answering Captain Robinson, I do not think there can be really any doubt that if the effect of one frame is added to that of another one placed at right angles to it—and the Bellini-Tosi patents surely point this out clearly—the result is the same as a frame at an angle to both these original frames. Furthermore, the Bellini-Tosi patent shows that reversing one of the frames is equivalent to moving the imaginary resultant frame through an angle equal to twice the angle between the imaginary frame and either one or other of the two actual frames. With regard to the alteration of sensitiveness, I might point out that if this is to be increased in the R.A.F. system, under practical circumstances it entails the reduction of the fore and aft coil (equivalent to increasing the leading angle between crossed coils) and a consequent loss of the so-called maximum signals. At the time the system designed by Captain Robinson was installed in aeroplanes I do not think the ordinary Bellini-Tosi system with tuned aerials could have been used, owing to the variable aerial tuning which it would have been impossible to avoid on an aeroplane. His design undoubtedly filled an important gap. I think, however, that on the larger planes the modern Bellini-Tosi system is preferable, particularly as it lends itself to large light aerials, direct reading in any direction, and easy correction for errors due to the aeroplane. Because of the possible electrical isolation of the receiver and receiving coils, it is very easy to free from magneto noise and magneto short-wave effects. The results so far have been very good, and although the operators have been provided with crossed swing coils in their radiogoniometers, they have reported that all signals are sufficiently good to enable ordinary swing readings to be taken with ease, the direction of Clifden being taken at a distance of 2,000 miles. The point raised by Captain Robinson about continuous wave reception does not enter, for in rotating the coil of a well-made radiogoniometer, connected as a self heterodyne as shown in Fig. 27, no change of interference note takes place when receiving from a continuous-wave station. This indicates that the energy absorbed by the aerials from the self heterodyne is constant for any position of the moving coil. It can easily be proved mathematically that this is true, but if further proof is wanted, no serious variations of direction ever took place in the day (except very isolated cases like the Nauen case mentioned) and these directions were remarkably correct. Immediately night arrived, however, everything went wrong except that the interference note was constant for all positions of the search coil. (The case mentioned by Mr. Ditcham is, however, worth noting, as he has had great experience of this work; but in hundreds of readings taken by myself on different nights I never noted this effect.)

I must apologize to Mr. Shaughnessy for the oversight in not mentioning the great aid given to me by his section of the Post Office. It has also been pointed out to me that I have not given the Marconi Company any credit for having allowed me to use anything and everything I wanted, and to take any men I wanted. I hope therefore both Mr. Shaughnessy and the Marconi Company will accept my apology. I remember very well that Mr. Hinton of Mr. Shaughnessy's section was the first man to point out the aperiodic nature of the plate-circuit coil in the tuner of Fig. 20 when used with no condenser, and to use this effect for quick searching. I think Mr. Shaughnessy's own stations were much more efficiently worked than my own, as I was usually considering the development rather than the actual operation.

In reply to Dr. Eccles, I have not seen Captain Brossier's reports, but I fancy that these are in some way connected with Lieutenant T. Eckersley's, as Captain Brossier knew of Lieutenant T. Eckersley's work. I am entirely unacquainted with any work done by the French during the war on direction-finding, except that I knew they were using frames in 1916. I am quite sure, however, that they had no such vast organization as we had, nor did they need it, as our war was first and foremost on the sea.

I am not quite sure whether Mr. Gossling is differentiating between separation of different signals, or the balance obtainable in one set of signals. A balance is obtainable at some point for any brilliancy of filament and any strength of signal, and an element of separating signals of different amplitude always exists owing to the lack of symmetry of the valve curve, but I think the results are never so good as with the dulled filament. In this case several sets of strong signals can be almost eliminated from one weak signal. I think the effect is undoubtedly a combination of balance and saturation, either predominating at the will of the operator.

In reply to Mr. Dowsett, I think my difficulty was that the original Bellini-Tosi condensers and the later coupled disc condensers developed by the Marconi works would not stand transport, and I am afraid that I and others were generally prejudiced against them on account of this, in view of the fact that the separate condensers we used could be easily balanced by means of a buzzer set.

I believe I have touched on the points mentioned by Major Vincent Smith elsewhere, but I must thank him for his very kind remarks.

ADDRESS TO THE STUDENTS' SECTION,

By ROGER T. SMITH, President.

(*Address delivered 5 March, 1920.*)

It has become a time-honoured custom for the President of the Institution to address the Students at or near the end of the active part of the session during which meetings are held and papers read and discussed. I feel that the present occasion is no ordinary one, and if I fail to do justice to it the fault will be mine and the loss will be yours.

Many Students of the Institution took their part in the war and won distinctions. 652 Students served in H.M. forces, of whom 67 lost their lives and 82 were awarded decorations or were mentioned in despatches. Now that peace with Germany is ratified, we are faced with the position that the world is clamouring for manufactured articles of every sort and description, but that many of our industries are not capable of supplying anything like the demand. This is one of many causes which keeps up the price of nearly everything we have to buy; but for machinery and for industrial products the need is so great, both at home and abroad, that these high prices are paid. In certain classes of electrical manufacture makers are so full of orders that they quote what they feel to be prohibitive prices so as to keep customers away, but the customers accept these prices and the manufacturers are at their wits' end to know how to make and deliver the goods.

These conditions are entirely abnormal and in some respects unhealthy. The profits may in some cases be large and the unthinking call it profiteering, but the order is forced on the manufacturer against his will by the absolute need of the purchaser who is willing to pay almost any price to get what he wants.

Such a state of things is far more pronounced in commodities which come first in man's requirements—food, drink, and clothing—than in electrical manufacture, but it exists to a considerable extent in electrical manufacture as well.

The position interests you vitally as Students because if, owing to the demand exceeding the supply, these high prices are to continue for many years, the prospect of employment for the educated and trained electrical engineer is likely to be rosy, since there is no doubt that the supervisory staffs in many establishments are overworked and more trained workers are required.

I do not believe that anybody's guess as to whether the present conditions of abnormal prices are likely to continue is worth the words which express that guess. Certainly I am not going to say whether I think it will take few or many years for the supply to equal the demand, because in my view there are insufficient data for forming an opinion.

But it is certain that this period of considerable profit is being used by many manufacturers to spend money out of revenue for enlarging their works and increasing or improving their plant, so that when the slump comes, as past history suggests that it must come, manufacturers' works ought to be equipped to compete in the world's markets in a way which they have not been able to compete within my memory.

Our electrical manufacturers have always been able to compete, and have competed in the past, first by the excellent quality of their goods, and secondly by cutting prices. It has been determined by an authority to whom the data for forming an opinion were available, that before the war the average profit of manufacturing electrical firms in this country was of the order of 1 per cent. In few cases was it possible to extend buildings and re-model plant out of revenue, or to devote money out of revenue to research, and the habit of struggling with small profits over a long period of years does not tend to make manufacturers use increased profits, when they do come, in the most far-seeing way. But the absorption of small firms by large ones, who have become larger through success, corrects or at least tends to correct the narrow view which the struggle for existence may have brought about, so that whether or not prices and profits fall within the next few years, I think there is good evidence to show that there will be increased employment for electrical engineers at fair salaries for some years to come.

I have only dealt with manufacturers. If there is an increased demand for manufacturers in an industry like ours, there is an increased demand and corresponding employment all round, both for engineers who make things and for those who advise or carry out composite works.

In the May number* of last year's *Journal*, in a very interesting and instructive article by Messrs. A. B. Gridley and A. H. Human on "Electric Power Supply during the Great War," it was shown that, whereas in 1914 the sale of electricity by supply authorities in the United Kingdom was 2,100 million units, this sale during the war was increased to 3,500 millions in 1917 and to the estimated amount of over 4,000 millions in 1918. This is quite apart from the great increase in private supplies in works and factories for driving the vast amount of machinery needed for munitions, for smelting or for other industrial purposes.

The Armistice put an end to much of this use of electricity, but it has not put an end to the habit then learnt, that the natural drive for the modern workshop is the electric motor. Industrial fashion does not change so quickly as some other fashions, and it is a matter of no little importance to the future employ-

* *Journal I.E.E.*, 1919, vol. 57, p. 406.

ment of present-day students that it is becoming the fashion to use electricity in industry as a result of the war to an extent that it was not used before the war, and, on the average, custom ranks before logic in this country.

Under the Electricity Act, 1919, one of the many duties of the Electrical Commissioners is to make the general use of electricity fashionable, and if they largely extend its use by doing so it will go far to counteract dearer coal and higher wages.

There is a custom in universities and other places of learning, to limit the use of the term "scientific" to a consideration of such facts as have been agreed to be called scientific—such facts as are considered in the schools and are readily reduced to exact analysis. And I am sure that this improper limitation of the elements which go to make up the whole engineering problem has had a good deal to do with the fact that many business men engaged in industry have looked askance at the employment of scientifically trained men because they have so often found that the training has not only omitted elements which the employer knows to be all important in conducting an industry, but has produced a habit of mind which considers certain facts to be unsuitable for scientific treatment.

Now the scientific method as applied to engineering consists in recognizing and collecting all the facts and then making deductions from them. Of the two the power to recognize all such facts as bear upon a problem is generally much more difficult to acquire than the subsequent analysis, and if we are really scientific we have no right to select only those facts which we have been taught how to deal with analytically.

If it be the case that fashion in the use of electricity is an important fact in the development of the electrical industry, it is just as scientific to include it among our premises and deduce what we can about it, as it is to determine the efficiency of the machinery we use or the calorific value of the coal we burn in our boilers.

And this brings me to a still more important matter in the training of an engineer which is usually considered to be unscientific; I mean the question of £ s. d. in relation to all engineering problems. Again I feel that most of our engineering and technical schools are at fault in not putting the cost of estimating and the cost of engineering work of every sort as an important element in their teaching.

The cost of things is in almost every case the most important of all the facts with which the engineer has to deal in every scheme which is entrusted to him in his profession. But in the scientific training of the engineer, measurement of physical quantities is generally alone taught. It rightly comes first because the mind is best trained for engineering problems by the exact measurement of physical quantities, but it is unscientific to ignore the measurement of money.

Every engineering problem involves or ought to involve money as its ultimate consideration, and the successful engineer is the man who employs the least capital on a job which in its working produces the greatest return on that capital. I claim that it is unscientific in the strictest sense of that word to ignore costs, both capital and revenue, in the training of the engineer.

I do not say that it is possible for universities and technical schools to teach the commercial side of engineering to the student. The time available is best employed in learning principles of measurement and the orderly habit of dealing with facts which can be measured more or less accurately. The costs of engineering work can best be taught in the industry itself. But it is possible for a student to complete his scientific training without any idea that the most important fact with which he has to deal in his engineering career is the cost of the scheme or of the machinery which he has to create.

It has been said that any fool can invent a thing but that it takes a genius to sell it. And, so far as manufacture is concerned, the art of selling is in general better paid than the art of design. The art of selling engineering manufactures demands qualities which the designer need not possess, but it is becoming more and more common to employ selling engineers who have acquired both arts. I cannot but feel that our universities and technical schools ought to lay the foundations of the commercial knowledge required by the engineer at the same time that they lay the foundations of technical knowledge. Little but the foundations can be laid, but if the commercial part of the engineer's work was treated as of the same scientific importance as the purely technical, it would at least stimulate the student to find out where the principles of commercial training can be learnt.

The London University has lately developed a commercial school which will grant degrees in commerce. The external side of the university will provide, for those who cannot attend full-time courses, commercial teaching intended for those at work in the daytime. The whole scheme has been carefully worked out by business men in conjunction with the University authorities. [For information apply to External Registrar, University of London, South Kensington.]

In his address to the Students' Section last November Mr. Trotter, in a paper * which I venture to think is worth reading more than once for its manner as well as for its matter, pointed out very clearly the difference between dealing with things, about which one can know a great deal, and with people, about which one can know very little. Judgments based upon what we think we know about people so often trip us up, and yet for many of you, as you rise in your profession, the art of directing the great sources of power in nature becomes more and more the art of overcoming the small-mindedness of man. It is not engineering but it is part of the art of living, an art which is not sufficiently studied in this country.

Few of you will rise to any eminence in your profession without having to control wage-earners and those who supervise them. For some time to come the personal relations between the individual employer through the employers' management and the individual wage-earner will become less and less the more rates of pay and conditions of service are settled by collective bargaining. Collective bargaining means that you pay

* *Journal I.E.E.*, 1920, vol. 58, p. 117.

the rate of the particular grade in which a man works and not the rate applicable to the abilities of the man himself, and while this method is probably the only method by which labour can get improved conditions, I cannot but feel that it will be superseded in the future by some method, possibly differing from present piecework schemes, which will make it possible to pay by results at rates settled by collective bargaining. That is now under consideration in the engineering trades.

By the time most of you are earning a salary, you will find an industrial world working under conditions entirely different from those prevailing before the war. The traditional war between capital and labour dies hard, but I hope it is not too optimistic to say that some of the causes of that war have been removed. I hope some of you may take your share in removing more of them. You remember that when someone exclaimed to Charles Lamb, who had been expressing violent hatred for a certain individual, "Why you hardly know him, how can you hate him?" The essayist replied, "How could I hate him if I knew him?" Part of the distrust of the employer by the wage-earner is only too well founded. Another part of the mistrust is simply due to mutual ignorance, and the constant meetings between the representatives of trade unions and of employers are all to the good in building up that confidence that agreements come to will be equally respected by both sides, without which collective bargaining is a farce. Now capital represents savings, and every man, or body of men, who saves and uses his money as a means of producing more is a capitalist. All the trade unions who invest their savings from members' contributions in securities are capitalists. Business is based on profit and loss, and the man, or body of men, who risk, and often suffer, losses ought to reap the profits when there are any.

The risk of loss is one of the chief stimuli making for efficiency in business, while the hope of profit is another. The critics of capitalism only look at the profits which they envy, and ignore the losses which they are not prepared to incur.

A government does not save; it only spends, and when it makes losses it looks to the people who are governed to make them good. And that is one reason at least why nationalization of an industry, by taking away from the management of that industry the stimulus of the fear of losses or the stimulus of profits, is generally inefficient under our imperfect civilization.

Granted an ideal of service in all classes, nationalization of an industry might be efficient, but the ideal of service is only imperfectly realized by the few.

If I have succeeded in interesting you in the importance of the study of the relationship between the wage-earner and the employer I would suggest that you study for yourselves the organization of employers and of wage-earners in the textile trades. I had hoped to have placed in the library some documents on the subject, but no published documents are available. The textile trades have probably been fully organized for a longer time than any other trades, and perhaps the engineering trades could learn useful lessons from that organization. Anyhow some of the details of that organization are available if any of you care to consult them.

As you probably know, the Whitley scheme for Joint Industrial Councils provides, for such industries as are organized, councils for collective bargaining and the settlement of disputes as a government measure. The scheme only recognizes organizations of employers on the one hand and the organizations of trade unions on the other. The salaried members of industry were left out. At the Industrial Conference called by the Prime Minister in April of last year at which employers' associations and trade unions considered the formation of a National Industrial Council, it was moved that when this National Council is formed the position of unions exclusively composed of administrative, managerial and technical grades should be considered with a view to such unions being represented on Joint Councils and on the National Council.

Whether the National Industrial Council will be formed or not seems to depend (at the time of writing) on whether Joint Agricultural Councils can be formed or not. Meanwhile the professional classes are unrepresented and unrecognized. This may or may not affect you. There are several trade unions for the salaried staff in industry. In some cases the Parliamentary Trade Union Congress refuse to admit them to the Congress and to recognize them as trade unions. I cannot feel that this refusal will ultimately be to their disadvantage, although for the present it restricts their membership, because if a trade union is not recognized as a trade union it is by some not considered worth belonging to.

On the 7th February a conference of representatives of professional associations was held in London and a resolution to form a federation of some of those bodies was adopted.

Although it appears necessary for protection purposes to have associations of technical salaried staff, I feel personally that to apply the principle of collective bargaining to salaries above £300 or £350 is wrong.

An employer does not pay £1,000 a year or more for a particular position, he pays the man, and I hope it will never come about in this country that salaries to technical, managerial or administrative men above £500 a year are fixed on any other basis than the value of the man to the employer.

The position of the technical salaried staff in industry is in the melting pot. It interests your future vitally and you ought to be considering it carefully and watching how things are going. But if you assist in eliminating personal bargaining for your own salary, you will I think be doing an unwise thing.

In the practice of your profession some of you will have to write specifications and all of you will have to write letters. The writing of specifications is an art by itself best acquired by long practice in the office of some engineer who has himself acquired the art. If the specification describes in detail the work that is to be carried out by a contractor or manufacturer, then the writer of the specification must be responsible for the result of the work when it is carried out. If, on the other hand, the specification asks for a result,

the engineer must not at the same time tell the contractor or manufacturer in detail exactly how the work is to be carried out. And yet it is quite commonly done. Certain parts of the work may be specified in detail, more especially the qualities of materials to be used, and it is quite proper to describe in detail one way in which the result can be achieved, provided you leave it open to the contractor to employ his own way and use his own standard types of machinery or methods of construction.

One of the things in engineering which is best learnt early, is the number of different ways in which the same result can be achieved. Sir Alexander Kennedy in his Presidential Address to the Institution of Civil Engineers in 1906, an address which deals with the engineer as a man and is well worth reading and re-reading at intervals, says: "From the day that his pupilage ends until the last day of his engineering life the engineer is always face to face with the fact that there are half a dozen ways of doing everything, and that the half-dozen ways are all more or less equally good." I believe that if everyone who specified engineering work learned that truth young, it would save them many mistakes and failures.

But I would plead specially for writing specifications and letters in English. It is fortunately less a habit than it was some time back for engineers and others to write specifications and letters in a jargon which was certainly not English. We have a very rich and expressive language which, unfortunately, we are never or rarely taught at school, as by contrast a French boy is taught French. And yet we have a wealth of English literature, from the careful reading of which an Englishman with much practice can learn to write English that is lucid and unambiguous.

The compulsory teaching of the classical languages in our older universities is dying hard, but there are signs that it is dying. It is to be hoped that if, by common consent, Latin and Greek cease to be compulsory subjects, English and French may replace them for educational purposes. But that will only be of use to your children. I therefore commend to your earnest consideration as one of the essential equipments of the engineer, the acquiring of a style of writing specifications and of writing letters which is as simple and as straightforward as you can make it. Should any of you have been taught English at school or in the university you are very fortunate. Never let it rust. But it is safe to say that most of you have had no chance of learning to write English, and to those I say it is incumbent on you as electrical engineers to acquire the art by noticing style in everything you read. But I warn you that as your taste becomes critical you will find it almost impossible to read a great deal which is otherwise harmless.

You are entering a great profession. I sincerely hope that many of you will leave your mark upon it for its good and for your own. The Institution has now, I believe, the largest membership of any of the engineering Institutions. You have done well to join it at the beginning of your careers and I hope you will render it loyal service. It is only the loyal service of its members of all classes which can keep the Institution great and make it greater.

The Address was followed by an interesting discussion in which 13 Students took part, most of the points touched upon by the President being discussed and amplified. The President also replied to some of the questions which were asked, and after the discussion showed a number of lantern slides illustrating the types of electrical machinery such as cranes, hoists, etc., which have been installed under his supervision on the Great Western Railway.

ANNUAL DINNER, 1920.

The Annual Dinner of the Institution was held on Thursday, 4th March, 1920, at the Connaught Rooms, Great Queen-street, W.C. The President, Mr. Roger T. Smith, presided over a gathering numbering about 400 persons. Among those present were:—The Hon. Sir Charles Parsons, K.C.B. (*President, British Association*), General Sir C. F. N. Macready, G.C.M.G., K.C.B. (*Chief Commissioner of Police*), Sir G. E. P. Murray, K.C.B. (*Secretary, Post Office*), Rear-Admiral Sir W. C. M. Nicholson, K.C.B. (*Third Sea Lord and Controller, Royal Navy*), Lieut.-Col. Sir F .Younghusband, K.C.S.I. (*President, Royal Geographical Society*), Major-General Sir A. M. Stuart, K.C.M.G., C.B., Sir John E. Thornycroft, K.B.E., Sir Sydney Chapman, C.B., C.B.E. (*Permanent Secretary, Board of Trade*), Sir Gregory Foster (*Provost, University College, London*), Sir William Slingo, Major-General G. D. Jeffreys, C.B., C.M.G. (*Officer Commanding London District, War Office*), Rear-Admiral F. L. Field, C.B., C.M.G. (*Director of Torpedoes and Mining, Admiralty*), Mr. H. A. Payne, C.B. (*Permanent Secretary, Board of Trade*), Mr. E. Raven, C.B. (*Second Secretary, G.P.O.*), Captain H. Riall Sankey, C.B., C.B.E., R.E. (*President, Institution of Mechanical Engineers*), Captain A. K. Waistell, C.B. (*Captain, H.M.S. "Vernon"*), Col. H. C. Sparks, C.M.G., D.S.O., M.C. (*Member of Council*), The Rt. Rev. Bishop H. E. Ryle, C.V.O., D.D. (*Dean of Westminster*), Sir W. H. Bragg, K.B.E., F.R.S. (*President, Physical Society*), Mr. W. W. Lackie, C.B.E. (*Electricity Commissioner*), Mr. C. H. Wordingham, C.B.E. (*Past President*), Mr. P. R. Allen, O.B.E. (*Member of Council*), Colonel O. C. Armstrong, D.S.O. (*President, British Engineers Association*), Mr. Ll. B. Atkinson (*Vice-President*), Mr. W. H. Booth, O.B.E. (*Electricity Commissioner*), Mr. H. F. Carlill (*Controller of Industrial Power and Transport, Board of Trade*), Mr. A. Carpmael (*Honorary Solicitor*), Mr. H. J. Cash (*Member of Council*), Mr. H. W. Clothier (*Member of Council*), Mr. E. Guy Dauber (*Vice-President, Royal Institution of British Architects*), Mr. J. Devonshire (*Honorary Treasurer*), Mr. D. N. Dunlop (*Member of Council*), Dr. W. H. Eccles (*Member of Council*), Mr. S. E. Fedden (*Member of Council*), Mr. A. P. M. Fleming, C.B.E. (*Past Chairman, North-Western Centre*), Dr. C. C. Garrard (*Chairman, South Midland Centre*), Mr. J. Gray (*President, Society of Chemical Industry*), Mr. J. S. Highfield (*Member of Council*), Mr. G. W. Humphreys, C.B.E. (*Chief Engineer, London County Council*), Mr. A. Hurst (*President, Institution of Railway Signal Engineers*), Mr. C. D. le Maistre, C.B.E. (*Local Hon. Secretary of American Institute of Electrical Engineers*), Mr. G. C. Lloyd (*Secretary, Iron and Steel Institute*), Mr. Stanley Machin (*Chairman, London Chamber of Commerce*), Mr. W. M. Mordey (*Past President*), Mr. W. Noble (*Engineer in Chief, G.P.O.*), Mr. A. Page (*Electricity Commissioner*), Mr. G. W. Partridge (*Vice-President*), Mr. C. C. Paterson, O.B.E. (*Member of Council*), Prof. J. E. Petavel, D.Sc., F.R.S. (*Director, National Physical Laboratory*), Mr. G. H. Roberts, M.P., Mr. T. Roles (*President, Incorporated Municipal Electrical Association*), Dr. S. Russ (*President, Röntgen Society*), Mr. J. Sayers, O.B.E. (*Member of Council*), Mr. W. M. Selvey (*Chairman, North Midland Centre*), Mr. A. P. Trotter (*President, Illuminating Engineering Society*), Mr. P. D. Tuckett (*Member of Council*), Prof. R. M. Walmsley, D.Sc., Mr. B. Welbourn (*Member of Council*), and Mr. P. F. Rowell (*Secretary*).

After the usual loyal toasts the President read the following congratulatory telegrams from the Associazione Elettrotecnica Italiana and the American Institute of Electrical Engineers:—

"MILAN, *1st March*, 1920.

"On behalf of the Italian Electrotechnical Association, I join in hearty wishes for prosperity of Institution.

"PRESIDENT FERRARIS."

"NEW YORK, *26th February*, 1920.

"Please extend to President and Members Institution Electrical Engineers greeting and felicitations from sister Society in America."

Sir GREGORY FOSTER, in proposing the toast of "The Institution of Electrical Engineers," said: I am deeply sensible of the responsibility that devolves upon me in proposing what is the toast of the evening. I imagine that one of the reasons, if not the main reason, why I have been selected for this honour is that I am the least electrical person in the room. I cannot therefore talk to you in technical language. The beginnings of the Institution were made in the year 1871, a year that was big with destiny for the world, how big we have only learned in the last five years. The Institution began, I understand, as the Society of Telegraph Engineers, which signifies, I take it, that in 1871 the main function of electricity in the world was telegraphy. In the 49 years that have elapsed since then lighting, heating, traction and wireless telegraphy and telephony have been added to the profession. Of these perhaps I know, by the happy fortune of my position, most regarding wireless telegraphy and telephony, because during many of those years I have been in close contact with my friend and colleague Professor Fleming. Perhaps I may interpose here, what I am sure you will all be glad to learn, that there is now every reason to hope that Professor Fleming will recover from his recent serious illness. In these 49 years the Institution's destiny has been a great one, and evidently it is by no means fulfilled. What electricity can yet do for the world is only a matter of conjecture. It is a wonderful thing to look back and see what it has done in those years. You, with your more intimate knowledge, can perhaps forecast what it will do in the next 50 years, and

can judge how this great science will throw out its tendrils in all directions. I wonder whether I am right when I say that the great progress which has been made is due, in the main, to what we may call team work. There have been great inventions, made by great inventors. Every one of them has been led up to and has been perfected by the industry of a vast number of others. I think the lesson that we ought to learn from the war is that in this country there is need for greater provision for the organization of research. We have done much in the last 50 years in the way of developing schools of engineering, but those schools of engineering, as I know, have grown up amid the greatest difficulties, with insufficient resources even to do the daily work connected with the training of undergraduates, and they have been very insufficiently provided with those requirements that are essential if research is to be organized, as it should be, for the progress of electrical engineering and of science in general. The Government has at last during the war shown some sign of being awake to this need. It has instituted a Department of Scientific and Industrial Research, and I think we may all hope that through that Department better organization of research will follow and greater progress be made than ever before. I wish your great Institution greater distinction and usefulness in the next 50 years than it has had even in the last 49 years. I have very great pleasure in proposing this toast for the personal reason that I am able to link with it the name of your President, Mr. Roger Smith. I have know him since the days when we were students together at University College. I have kept in touch with him ever since, and you who know him will, I feel sure, share with me the feeling that he is a man we admire and love. I congratulate you on your President, because I know that he is a leader, and I give you the toast of "The Institution of Electrical Engineers," coupled with his name.

THE PRESIDENT (Mr. Roger T. Smith), in responding, said: I thank Sir Gregory Foster very heartily for the way in which he has proposed the toast of "The Institution," and also for the kind words that he used towards me as an old student of University College, of which he is the distinguished Provost. The scientific training of engineers and, above all, of research workers, is of the very greatest importance to the electrical industry. University College has decided to re-build its engineering school and to re-equip its mechanical and electrical laboratories, and other Universities either have done the same or are prepared to do so when the need arises, in order to achieve the great educational effort which is really necessary for the progress of electrical science and for the proper training of the present generation of electrical engineers. I thank this great assembly for the way in which they have honoured this toast. It is very appropriate that the number present at this Dinner—I understand that it is over 400—should exceed that at any previous Dinner, because I believe that this month the Institution will have a membership greater than that of any other engineering institution in the United Kingdom. Next year the Institution will celebrate its fiftieth birthday, and that event, coupled with our great membership, ought to stimulate us to take to heart Sir Gregory Foster's words and to determine that the education of engineers and the education of research workers shall go forward. Satisfied as we may well be with a membership which this month will amount to 8,800, we ought not to be proud of that membership unless every member is determined to make himself more and more efficient in the art of electrical engineering based on a sound scientific and general education. The greatest electrical event during the present Session has been the passing of the Electricity Supply Bill, and I think that the most important provision under the Act is the provision of five Electrical Commissioners, four of whom have been appointed and were to have been our guests to-night. Unfortunately they are not all here. Sir John Snell asked me to say that he deeply regrets that circumstances over which he has no control have made it impossible for him to be present. But those who are here we welcome. I hope the Institution may be able to render such services as it can properly render to the State and to the electrical industry in the carrying out of the Act. No Act altering the existing state of things can but be unwelcome to individuals, and to some entire sections of the electrical supply industry. But the Institution, however imperfectly, strives to represent all sections of the industry, and, just because it represents minorities as well as majorities, occasions may arise when it may serve a useful purpose as a clearing-house for misunderstandings. If such an occasion should arise, I hope the Electrical Commissioners will not forget that the Institution is at their disposal. Whatever our views may have been of the Electricity Bill, and however freely some of us may have expressed those views, that Bill is now an Act, and the Institution hopes very heartily that the administration of that Act may result in the benefits which were intended when it was promoted, namely, an abundant and cheap supply of electricity. Within the Institution itself perhaps the most interesting feature of the last few years has been the steady de-centralization of some of the efforts of the Institution by means of Territorial Centres and Sub-Centres. There are now in the United Kingdom no less than 12 Territorial Centres and Sub-Centres, while abroad there are two in existence and more in contemplation. Sheffield, Liverpool, and the East Midlands have all been formed as Sub-Centres during the present Session, and the movement exhibits a natural growth tending to the development of local activities which is wholly good. The parent body in London, approaching middle age with cheerful resignation, is delighted with the vigorous exhibition of enthusiasm by these local bodies. Happy in the stored traditions of very nearly half a century, it is flattered that there should be a proposal for a London Centre, or was it a Sub-Centre to Manchester? I must remind you, however, that the 3,000 odd members who would form that London Centre are equal to the whole of the membership of all the other 12 Centres and Sub-Centres; and unfortunately we cannot for financial reasons afford to form a Sub-Centre in London. Every Centre and every Sub-Centre costs money, and when we return, as I hope we may do in the course of this summer, to our own building on the Embankment, the great difficulty that will face the Institution at once will be the question of finance. Expenses

have gone up and, heartily as I am in agreement with the territorial constitution of the Institution involving the making of Sub-Centres to the existing Centres, that is only going to be satisfactory if it is clearly understood that all these things cost money and that the members are prepared to meet that extra cost. Dealing with matters outside the Institution as well as inside, what we have all looked forward to, and what we all now want is peace. During the war many sailors afloat, many soldiers at the front, and many civilians at home, were perfectly at peace within themselves because they were performing service, service which often involved personal loss—money, health, limbs, life—and untold numbers were perfectly at peace with their own souls because that service was gladly given. Now that peace is signed, at least with Germany, the whole of the world seems to be in a state of unrest, and that is at least partly, if not wholly, because the idea of service seems to have departed from entire sections of the community. I believe that the secret of peace is service. I believe that until the idea of service, such service as is freely given for example by our King and by the Prince of Wales, replaces the idea of narrow self-interest and, above all, of class war, we shall never have real peace. The Institution—and I speak to my fellow-members—is a great body with a great inheritance. It offers you all an opportunity to keep it great and to make it greater by your unselfish service in its interests. I commend that service to you.

Mr. Ll. B. Atkinson, Vice-President, then proposed the toast of "Our Guests," to which General Sir C. F. N. Macready, G.C.M.G., K.C.B., and Lieut.-Colonel Sir Francis Younghusband, K.C.S.I., responded.

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DISCUSSION ON

"FAILURES OF TURBO-GENERATORS AND SUGGESTIONS FOR IMPROVEMENTS."*

NORTH-WESTERN CENTRE, AT MANCHESTER, 13 JANUARY, 1920.

Mr. J. S. Peck: On page 127 the author refers to the open-core construction as being weak. I think this depends entirely on the kind of supports which are put in to form the vent ducts and to secure the teeth at the ends of the core. If very strong supports are used, and if suitable methods are adopted for pulling up the laminations, the core with radial vent ducts should be quite as rigid as one can desire. On page 128 it is stated that: "The electrical weaknesses in turbo-alternators have generally developed since the size of the machines and the systems to which they were connected increased to over 30,000 kw. on a single set of busbars." This is not my experience. I think there were more troubles in the early days of turbo-alternators than there are to-day. We have profited a great deal from our failures on the early designs and, in spite of the enormous increase in the number of machines in operation, the total number of troubles in 1919 was probably considerably less than in 1909. Regarding the method of joining the bars, through the slots, to the end connectors, we have found it better to use sweated joints. We tried several machines with welded joints and our conclusion was that the same reliability could not be placed in a welded joint as in a sweated one. It is extremely difficult with a conductor of fairly large cross-section to ascertain whether a weld is perfect, whereas by careful workmanship and inspection it is usually possible to guarantee a sound sweated joint. With regard to laminating the stator bars, our general practice is not to laminate so finely as some makers do, but to transpose the bars inside the slot so that each bar occupies a symmetrical position in the slot. In this case the ends of the parallel conductors can be sweated together at the ends, and a solid end connector used. In the section headed "Heating and Fire Risk" the disastrous results which often happen when a breakdown occurs are pointed out very vividly. I think there are two methods of attacking this problem in addition to the method suggested by the author. One is to use fireproof insulation on the end winding. I suppose all makers have considered and perhaps attempted it, but so far no thoroughly satisfactory fireproof insulation has been found. The other method is to use automatic devices which, in the event of trouble occurring in the alternator, will instantaneously disconnect the machine from the busbars and at the same time break the field circuit. The latter method is now becoming more or less general practice. Success in preventing ignition of the insulation seems to depend upon the rapidity with which the machine can be disconnected from the busbars and the field circuit broken. The machine may be disconnected from the busbars, but if the field is left on, or if it takes a long time to die down, the fault is fed and a fire is likely to be started. What little experience we have had with breakdowns where this device has been used seems to indicate clearly that the fire risk is enormously reduced. On page 132 it is suggested that a great deal can be said in support of a temperature of 150° F. Under the British Standard Specification, with an air temperature of 40° C., this is equivalent to a rise of 25 degrees C. We generally assume in this country an air temperature of 25° C., which would make an allowable rise of 40 degrees C. The temperature rise of a turbo-generator is often specified as 40 degrees C., but no one, I think, would give such a guarantee if it meant that the hottest part of the machine was not to rise in temperature more than 40 degrees C. It may be possible to get a machine with 40 degrees rise shown by a thermometer, but everyone knows that the internal temperature-rises are much higher than 40 degrees. We also know that many machines have been in successful operation for many years with temperature-rises very much in excess of this value. It is

* Paper by Mr. J. Shepherd (see page 125).

comparatively easy to make a design which looks very simple on the drawing board, and, when studying a drawing, I have often been misled into thinking that something could be done, only to find out after inspecting the actual machine how badly I had been mistaken. In Fig. 10 the coils are shown lying beautifully in the coil supports, but however well we may insulate the coils, and although we may with open slots insulate the coil completely from end to end, there are still the joints between the coils which must be insulated after the coils are in position. It is an extremely difficult thing to insulate these joints so that they can be clamped against the metal coil supports. With regard to the construction in Fig. 9, I see a good many difficulties there, but I will only say that my chief objection to a band of the kind proposed by the author is that an arc on the band will probably burn through a ribbon and the whole band will then unwind. Such a thing may easily result from a breakdown in the stator winding. As the author states, water cooling has been used on rotors. On the stator, however, as far as I know, no one has had the hardihood to try it, and certainly it is a very much more difficult problem. Welded or fused joints are very treacherous. One cannot be sure from an inspection that they are sound; and although we may test them out individually after the material has been handled, there is a chance that the joint may start leaking and, once this occurs, disaster is almost certain to result. The condition is very different from that of a pipe line, where a leak causes no particular harm and where it is accessible and can be readily repaired. I should have great hesitancy in attempting to build a machine with hundreds of joints which must be water-tight, but I should very much like to see someone else tackle it, for if he were successful it might mark the beginning of a new era in turbo-generator design

Professor Miles Walker: This is a paper of a kind which is too seldom put before us. A user comes forward and explains his objections. If designers knew more of the user's objections we should be much better off. The author also makes suggestions which I think are sufficient to claim our interest and turn our minds into useful channels. Some of them of course are not quite new. The author has put forward very clearly in the paper exactly why water cooling is so attractive. The facts have been before engineers now for many years, and have successfully been worked out in rotors. It remains now for the engineer to see how they can be worked out in stators. In applying water-cooling to stators the fundamental difficulty is this. If we use a perfectly closed metal pipe (which can of course be made watertight) we are in danger of currents being generated in the pipe. If, on the other hand, we break up the pipe into insulated sections then we are in danger of leakage. The author himself recognizes that difficulty. I should like to ask him to say in reply whether if one of these generators is built according to his drawings he will be the first person to buy it. The suggestion that a very high-resistance metal can be used in making bands on clamps or coils I think is a good one. I myself do not know of any very really high-resistance metal of sound mechanical properties. The very high-resistance alloys are rather troublesome from the mechanical point of view. If the author can tell us of some really good resistance metal having, say, 50 times the resistance of copper, and if he can say it will not crystallize, but retain its mechanical qualities, that will be a useful thing to apply to our present generators. The paper is full of suggestions and to each of them there arises, I think, a fairly obvious objection. The author is fully alive to many of these objections. At the same time these suggestions lead us to consider whether anything can be done. Water-cooling or fluid-cooling of stators will probably come in the future. The A.E.G. has successfully applied water-cooling to the frame. If we can get the iron into contact with a stone-cold stator we have gone a long way to get rid of a lot of heat. The application of water-cooling to the end connectors is a very difficult problem, and I am afraid that the author's suggestions will not go far enough. With regard to the question of the amount of saving effected by using the heat from the cooling system, one must always remember that this energy is received in the form of heat at a low temperature, not in the form of electrical energy. Such heat is generally worth very little; it may be worth something but it will surprise me if the case he gives works out at a capital value of £17,000. The losses are electrical. In order to get the energy from the lukewarm water we must pass it through a heat engine. If we work out the value of that in money it is worth very little. It is worth something like 5 per cent of the value of the electrical energy lost.

Mr. G. F. Sills: I presume the idea of the author in reading this paper is not only to bring new ideas before us, but also to review old problems and to see if satisfactory solutions have been found in to-day's practice. Concerning the question of critical speed, I think that any trouble from this cause has been very rare. The author advises steel-tape bands on the end of the rotor; at the same time he decries steel-wire bands. In event of a breakage or burning through of steel-tape bands, the same unfortunate result comes about. The author rather doubts the qualities of the steel rotor end-rings, pointing out that we do not know that the steel is as good as it ought to be. We might carry this argument further and say that the rotor steel is not reliable. We think that to-day the first-class steel manufacturers can give us sufficiently reliable steel. The author mentions possibilities of side-slip of rotor coils. The coils must be most accurately formed so that the coil actually occupies a radial position in running, otherwise undue stresses are set up. Trouble has been occasioned, in a few cases, through the movement of the rotor coils in an outward direction; but this difficulty has been eradicated by the use of powerful clamping devices during manufacture. I believe that all makers originally used packing between the rotor coils, but gradually gave this up as they improved their methods of manufacture. The author attaches great importance to the stator core. Speaking generally, in the past a certain amount of trouble has resulted from insufficient care in building up the core. Very large machines sometimes necessitate the cores being built on site, but when this is the case it requires great care to make such a good job as can be made at the works, where the core after being built up to a certain depth

should be oven-heated and pulled up, and this process repeated 3 or 4 times. It is of the greatest importance that very accurate dies should be used for laminations. One large electrical firm was well known during the war for the excellent work of their tool and jig room for some of the well-known aero-engine makers. The practice of one firm is to remove burrs from every lamination, then varnish both the paper-insulated and bare sides. It has been usual to use cast iron for the main end-plates in the stator core, but one maker is now using heavy cast-steel end-plates. I am not referring to the teeth end-supports. Reference has been made to the solid stator conductor. When two bars per slot can be used and each slot be made into three compartments, a solid conductor can be fitted into the compartment furthest from the air-gap, the middle compartment left free for ventilation, and the outside compartment fitted with a laminated form of conductor, drawn into a rectangular copper tube to give the necessary strength. This arrangement gives better ventilation, is mechanically more robust, and has given good service on machines up to 6,000 kw. In the first two paragraphs on page 129 we are first informed that to use a number of strips to form a conductor in one slot conduces to mechanical weakness; then we are told how important it is to have mechanical strength. We need to try the happy medium. The author queries the main terminal arrangements generally used. It is probable they could be improved. Mr. Peck mentioned that the automatic gear would, or should, disconnect a machine practically instantaneously, and an improvement was to use an automatic field switch. There is on the market to-day a further improvement, viz. a field switch not only automatic, but a reversing field switch which, after opening the shunt field of the exciter, again closes the circuit, but in the reverse direction, so that what might be termed a suicidal condition results. With a high-speed exciter there is a tendency for the exciter to continue generating due to the action of the commutation poles, even after the shunt field has been broken, and the above arrangement ensures the dying away of the alternator field. The author gives figures of the amount of dirt collected by an air filter. I do not know if it has been tried, but by taking the air through first a wet air filter and then a dry air filter, it would ensure a supply of cool and clean air. The dry air filter need not be extra large and the cleaning periods could be reduced considerably. The cost of an extra filter is only a fraction of the cost of the generating set. The author mentions temperature rise. This question is generally governed by price considerations. The British Engineering Standards Association's recommendations suggest a machine rated for the maximum continuous load it will carry. The very important subject of joints is raised. This trouble should not arise if an ample safety factor is allowed for in the surface area available for soldering. Welding the joints can, of course, only be used on relatively thin conductors, but, in the event of trouble, would be a disadvantage. Fig. 8 (*f*) is put forward as a patent of the author. Two days ago I was reading a patent granted in 1908 for the same idea, but with a dovetail wedge in place of the piece of parallel metal shown in Fig. 8 (*f*). It is questionable whether it would suffice to weld the top of a parallel key. A better construction would be to use a dovetail key, and then to weld on the top to make it watertight. Coming to Fig. 9, a considerable amount of metal in the middle of the rotor poles is shown without any cooling slots. It might be advisable to continue the water slots all round, as this would give a better average temperature in the rotor body. As regards manufacturers taking up this type of water-cooled turbo, the makers have to consider whether engineers generally will agree to this rather radical departure, apart from the difficulties of manufacture.

Mr. G. A. Juhlin: There are many valuable suggestions brought out in the paper, as well as severe criticisms, and I am afraid the author takes an unduly pessimistic view of the situation. A close study of the latest practice will, I think, show that the points in designs which the author criticizes have been effectively dealt with. There are a few points to which I should like to refer in detail. The author comments upon the difficulties experienced due to side-slip of rotor coils. It would be interesting to hear how many cases of trouble of this kind have come under his notice. I have never come across a case of side-slip in a properly constructed rotor, and if the coils are correctly formed and properly assembled no trouble will be experienced. One may well agree with the author that if the coils were supported at the ends as well as in the slots, more stability would be obtained, and I have no doubt that if experience had shown this to be necessary it would have been done. Rotor end-windings have been enclosed in iron, although not from the point of view of supporting the coils against side-slip. The slide which the author exhibited showing the rotor construction does not represent up-to-date practice, and should not therefore be taken as typical. With regard to the question of air dampers, we find from experience that if dampers are fitted in addition to field-breaking switches, fire can be prevented. In this connection, the closed air circuit with coolers has an advantage, as the oxygen in the air would soon be used up and the fire could not spread. Referring to ventilation, the author says: "Whichever method of producing the draughts is used, the correct distribution of the air after entering the machine is a matter of difficulty." That is correct, but I think it should also be realized that at the present time we are able to build machines with perfectly satisfactory distribution of the cooling air. Recent tests made on large generators indicate an exceedingly uniform temperature all along the core, which shows that the air distribution is satisfactory. In connection with the rotor the author refers to the difficulties of finding a suitable insulation to withstand the stresses. Mica, as the author shows, is so strong to withstand pressure, that the copper is damaged before the mica. If the mica can stand these stresses, I do not think there is much danger of its being damaged under normal conditions of running. The question of loose cores has already been mentioned. I think we may safely say that that is a thing of the past. The author advocates bolts through the core. This construction has been used for a number of years and no difficulties with loose cores are experienced. In connection with the stator winding, the author showed slides

and criticized bracing by means of sectors of fibre. Fibre may not be an ideal material from a mechanical point of view, but experience has shown that machines constructed in that manner will withstand short-circuits at the terminals. In Fig. 7, curves are shown which indicate the life of the insulation at various temperatures. Recent information shows that mica insulation as used on turbo bars will withstand much higher temperatures than those indicated in these curves. A paper read by Mr. Newbury before the American Institute of Electrical Engineers gives some very valuable results on that question, and it is of interest to note that American practice is to guarantee an ultimate temperature of 150° C. for mica insulation. We ought to be grateful to the author for some of the suggestions he has brought forward, but we may offer some criticisms as to the various means adopted for obtaining the ideal machine he describes. On page 133 he says: "If the modifications do not introduce other difficulties either in construction or in operation." To my mind that is the crux of the whole position, and I am of the opinion that possibly greater difficulties may be met with than those now existing. The author says that by means of water cooling it is easy to adjust the water flow so as to give a uniform temperature and thus eliminate hot spots. In Fig. 9, end windings are laid in slots all through. I do not think full appreciation has been given to the fact that the greatest drop of temperature takes place in the insulation and in the air spaces between the copper and the insulation, and between the insulation and the cooling coils. It seems to me that a great quantity of insulation will be necessary on the ends to make it safe from mechanical damage, etc.; moreover, it will be exceedingly difficult to place the coils in position with them lying in slots throughout the whole length. The author gives a table showing the relative thermal conductivity of mica insulation and air to be about 16 to 1. A small air space therefore will give a very large temperature drop. I am rather of the opinion that the temperature of these end windings may be higher than in an air-cooled machine. A machine built on somewhat similar lines, but air cooled, indicated clearly that the temperature drop at this point was high. In Fig. 10 the author deals with the stator. The same remarks hold good as regards the question of temperature drop through the insulation. It seems to me an exceedingly difficult thing to get close contact between the supports of the coils and the coils themselves. If the outside coils were made tapered it would be possible to get the coils clamped tight and so obtain good contact with the projections holding the coils in position, but even that I think would be an exceedingly difficult thing to do. A great thickness of insulation would be required on the ends, and in all probability the temperature would be higher than could be obtained in an air-cooled machine. Another very serious difficulty which is introduced by the coil supports is the question of expansion. The author claims that the coil supports shown will give the coil freedom of expansion, but it seems to me there is no possibility for the coil to expand, as the ends are clamped over the whole length. With the usual types of coil supports, a certain amount of expansion can take place without danger to the insulation. With regard to the claim that the author makes for the saving due to the heat in the water being utilized, there does not seem to be any advantage in this respect over the air-cooled machine. In several cases the hot air from a machine has been taken into the boilers, and by that means the heat has been utilized.

Mr. H. C. Lamb: The idea of collecting the heat from the generator by use of the condensate and recovering it in the water feed is, at first sight, a very attractive one, but in a modern station, equipped with the best methods of heating feed water, the saving on the coal consumption would amount to something less than half of 1 per cent. It seems to me quite evident that this matter will be decided by other considerations altogether apart from efficiency. Boiler plant in modern stations is generally equipped with fan draught, and there is a tremendous amount of grit turned out from the chimneys. Cloth filters involve a great deal of trouble and expense for cleaning and renewing the cloth, which very soon rots. Wet filters are also heavy in maintenance costs, so that, from one point of view, the water-cooled machine is certainly the ideal. It seems to me, however, that the author, in order to make good his case for water cooling, has, quite unintentionally of course, given an exaggerated importance to the dangers and troubles which exist to-day with air-cooled machines, and such an impression is very bad for the nerves of engineers who are in charge of the operation of plant. I thought it might be of interest to give the records of certain plant with which I have been connected for a number of years. This turbo-generator plant has grown during the last eight years from 20,000 kw. to 100,000 kw. to-day. During that period, with this plant there have only been two cases of faults on stator windings, and in no case could the fault be attributed really to the alternator itself. In one instance the turbine thrust-block gave way and allowed the rotor fan to foul the end casing, from which a piece was broken off. It fell across the terminals of the alternator and the set was automatically cut off from the busbars. At the same instant the field current was cut off and the damage done was comparatively trifling. It did not take long to repair it. The second instance in those 8 years was not really the fault of the alternator. Through an accident some steam was turned into the air intake and naturally the alternator broke down. But even that did not result in the disaster which the author rather led us to think is certain to occur. Again the damage was repaired in a very short time. It simply meant renewing some of the end connections. In the period of 8 years there have been two cases of rotor faults. In one case the rotor test indicated an earth. It was during the war and as the machine could not be spared it ran on for two years with that earth on the winding. When it was eventually sent away for repair it was found that the fault was due to the windings moving in the slots and it had to be entirely rewound. The other rotor fault was also quite a small matter of insulation breakdown on the end turns. These generators, 10 in number, have many times been on short-circuit. In some cases the faults have been right on the busbars, and the evidence of short-circuit has been

very plain in the amount of copper burned away, but so far as we have been able to discover, never in any case has any winding suffered on account of this short-circuit. We could never trace any movement of the coils or the end connections. For overhauling we have simply found it necessary to clean the windings thoroughly, blow out all the ventilation slots, and re-varnish the machines annually. If the period were carried back to 10 years instead of 8 years I should have to admit four more cases of stator faults. One of those was due to a defective joint. All the joints on these machines are sweated, and that is the only instance of trouble due to a defective joint. The other three faults in those 2 years were all due to the burning out of the cotton insulation between the turns of the winding. In two instances this led to very serious short-circuits between phases. Still it was not so bad as the picture which the author has drawn. There was not in any instance any difficulty in tracing exactly what was the cause of those faults. These machines at that time (10 years ago) were wound with cotton insulation between the turns of the winding. They were re-wound with mica insulation and there has been no instance of trouble on the stator windings during the last 8 years. The author compares very unfavourably modern high-speed plant with the low-speed plant of former times, but my experience is certainly different from his. In a low-speed 17,000 kw. plant, over a period of 15 years, the number of faults which occurred was really very great; there must have been during that time 40 or 50 stator faults. That of course was not due to the low speed; it was entirely due to failure of the cotton insulation on the turns of the winding in the slots. When the field current was quickly cut off, these faults were confined to one or two coils. In some cases they spread to a number of coils with very heavy short-circuits between phases. It may be of interest to give the figures for maintenance costs for turbo-alternators as compared with low-speed plant. During 8 years the maintenance costs for plant which is now 100,000 kw. works out at 0·3d. per 1,000 kw.-hours. For comparison the maintenance costs of low-speed generators for 15 years worked out at $1\frac{3}{4}$d. per 1,000 kw.-hours, i.e. 5 times as much. I think that the author showed on the screen the fine reciprocating plant of the London County Council generating station at Greenwich. We have in Manchester one of the two largest low-speed machines which were ever built, 4,000 kw. It is still standing and, occasionally, running. I hope it will remain for a long time to come as an interesting monument illustrating the engineering practice of the past.

Mr. H. A. Ratcliff: On page 129 the author deals with the question of internal versus external reactance. I cannot altogether agree with his conclusions, but I think it is very largely a question of the point of view. One aspect of the matter deals with the subject purely from the point of view of protection of the machine itself, and the other from that of the maintenance of continuity of supply. I think the second is perhaps the more important consideration, but it is really a case of the greater including the less, and nowadays when so many stations are running up to the full capacity of the plant installed, the two are to some extent identical. I consider that internal reactance by itself does not give quite the same protection to the system, and I doubt very much whether it gives the same protection to the machines that, under normal conditions, would be provided by a certain amount of suitably disposed external reactance. I take it that reactance is intended to be the final protection when everything else fails: when switchgear, relays, and other devices fail to operate, reactance is looked to as the ultimate safeguard, and, further, in this connection it should be observed that the protective action of reactance is instantaneous and therefore effective long before any electro-mechanical devices could possibly operate. That being the case, it is necessary that the reactance should be disposed so as to protect the system as well as the machines. Internal reactance will protect a machine in the event of a short-circuit across its terminals, but the shock caused by the other generators and synchronous substation plant feeding back to the terminals of the faulty machine will have most disastrous results upon the system. I consider, therefore, that the better plan is to have a moderate amount of reactance in the machine circuits, say from 10 to 15 per cent—preferably partly external—and in addition to divide the system suitably by means of reactance coils located either between the busbar sections or between the busbar sections and a common tie-bar or some such equivalent arrangement. External reactance undoubtedly possesses one possible advantage: the enormous current-rushes under abnormal conditions result in the setting up of intense electromagnetic fields in the reactive portions of the circuit, and these fields exert enormous mechanical forces on the conductors forming the reactive portions of the circuit. There should therefore be some advantage in removing the reactance fields and the resulting mechanical strains from the machines, and in transferring them to apparatus which has been specially designed to deal with such electro-mechanical forces. After reading the paper it appears to me that it does not matter very much whether we have 1 per cent or 50 per cent reactance in a machine; for if a fire is once started, however small the extent of the original cause, it would appear from the author's vivid description of such an occurrence that the machine is practically doomed to destruction. It would be a very good scheme, if possible, to construct machines so that internal faults would necessarily develop as faults to earth instead of as faults between phases. If that could be done the protection of machines would immediately be very much simplified. The efficiency of these large turbo-generators is now of the order of 95 per cent or more, and therefore there is not very much further improvement to look for so far as the alternators themselves are concerned, and it will consequently have to come from the driving end of the combination. The author refers to the relative importance of reliability and electrical efficiency, and I fully agree that in view of the enormous importance of maintaining continuity of supply (particularly in industrial districts) it would be most unfortunate if, for the sake of a more or less illusionary 1 per cent in the efficiency, designers sacrificed anything likely to reduce the mechanical robustness of generators.

Mr. J. A. Kuyser: I want to call attention to a

point in connection with the heat drop through the insulation. The author deals already with this on page 137, where he says, "the increased cooling might be in excess of the capability of the remainder of the machine to transmit the heat to the cooling ducts around the copper." I agree with the author on this point and believe the insulation presents a great difficulty in the development of water cooling. The greatest future for water cooling is, I think, in the cooling of the rotor, as there is no difficulty in cooling the stator by air for a machine of large dimensions. In the case of a rotor cooled by air the temperature rise may be, say, 100 degrees C.; of these 100 degrees, approximately 70 or 80 degrees represent the heat drop through the insulation, the remaining 20 or 30 degrees represent the temperature rise of the iron. If water cooling is used, the temperature rise of the iron may be reduced to 5 degrees C., which means a reduction in the total heating of 15 to 25 per cent, corresponding to an increase in current output of the rotor of 7 to 12 per cent. To get a real benefit from water cooling it would therefore be advisable to reduce the heat drop through the insulation, at the same time as the cooling of the iron is improved. This can be done by increasing the number of slots and increasing the surface of the insulation. An increase in the number of slots means, however, increased mechanical difficulties. Another way to deal with the drop in the insulation is to use oil cooling instead of water cooling, and bring the oil into direct contact with the copper. If this were possible, very high current densities could be obtained. Some years ago I looked into the possibility of oil cooling, but, on account of the difficulties of keeping joints oil-tight, the scheme was not further considered. In connection with the construction shown in Fig. 8 (*f*), the slot is closed by means of a plug, and the plug is welded. This construction looks somewhat weak. Due to the rotation of the rotor the cooling water is subjected to centrifugal forces, and a hydrostatic pressure is created. If the rotor diameter is 30 inches at 3,000 r.p.m. this hydrostatic pressure will be roughly 1,000 lb. per square inch, and this pressure acts on the filling piece. I would suggest the use of a wedge-shaped filling piece. In this connection another point requires further consideration, namely, in Fig. 9 the joint between the bronze coil support and the steel rotor. The hydrostatic pressure at this joint would be roughly 750 lb. per square inch, and difficulties can be expected in keeping the joint tight. But in addition there is a tendency due to the static pressure to press the bronze coil-support away from the rotor in an axial direction. The force acting on the support from this cause is roughly 35 tons. The coil support is prevented from moving by a ring screwed on the shaft end, but in view of the continuous vibration it is doubtful if this will prevent all movement and also leakage of water. With regard to the stator winding, the author recommends a continuous mechanical support, and in the construction illustrated in the paper an excellent support is provided. The difficulty would be to insulate the end connections sufficiently, as they are in direct contact with metal parts, and it is not possible to use "Micarta" insulation as for the straight part of the slot. For this reason most manufacturers prefer to keep the end connections away from iron by blocks made of wood or mica. The author exhibited a slide showing the stator winding of a 25,000 k.v.a. alternator of my design. In this type of winding a practically continuous support is provided for the winding. The stator bars outside the core are supported by strong fibre segments which prevent bending and cracking of the mica. This particular generator was subjected to a short-circuit at the busbars without any damage to the winding. As regards the design of the stator conductors, I quite agree with the author's recommendation to use a less drastic division. The winding should be designed so that the eddy currents are a maximum from the bottom of the slot to the top of the slot; this means lamination of the conductors near the slot opening, and solid conductors in the bottom of the slot. The end connections should, if possible, not be laminated at all. I have proposed an improved form of winding in which the conductors are laminated and twisted in the slot, each laminated conductor being connected to a solid end connector (patent 129788/1918). This winding has proved very successful after several years' experience. The 25,000 k.v.a. machine which the author showed as a slide, has a single conductor per slot, consisting of 11 laminations; these laminations are divided in four groups, each group being twisted in the slot, and each group connected to a solid end connector. Special connections between successive poles prevent currents between the four parallel circuits. The autho mentioned several defects of the air-cooled machines, amongst others the fire risk. This is closely connected with the method used for air cleaning, and in this connection I believe the future system will be the air-circulation system, in which the hot air coming from the generator is cooled in a surface cooler and re-circulated through the machine. This system does away with all difficulties in air cleaning and fire risk. The author mentions the impossibility of equal distribution of air and the presence of hot spots. In this connection I will give some results of a test made on the previously mentioned 25,000 k.v.a. machine. The test was made at 30,000 k.v.a. until the temperature was constant. The temperature rise of the stator core was measured over the whole length. The following are the observed figures 26–29–30–34–33–32–38–34–26–31–28 degrees C. As will be seen, the temperature was very uniform. The maximum temperature rise in the centre is only 20 per cent above the average rise. The system of ventilation used is of the radial axial type as described in the *Journal* (1916, vol. 54, p. 178).

Mr. K. Baumann: At the top of page 136 the author says: "The whole of the heat losses in the alternator would then be utilized." He has made it more clear to-night by stating that the saving effected on a 10,000 kw. set is £17,000 capital value. I should be very sorry if anyone went away with a wrong impression as to the possible saving, and I will prove that the saving is not £17,000 but £1,700. The heat in the alternator is at a very low temperature and is of very little commercial use. The reason why we introduce heat into a power station is to produce mechanical work, and the value of the heat must be measured by the amount of mechanical work

it is capable of producing. The temperature of the condenser may be raised from 80° F. to 90° F., and heat at this temperature is obviously not of much use for producing mechanical work. There is, however, a more accurate way of proving my point. The commercial value of heat can be measured by the amount of mechanical work which must be sacrificed to produce a similar amount of heat at the same temperature. With an alternator efficiency of 95 per cent and a thermal efficiency of the plant of 20 per cent, the heat due to the losses in the alternator represents 1 per cent of the total heat in the coal. A similar amount of heat of low temperature can be obtained by sacrificing very little mechanical work in the following manner. In a 10-stage turbine about 1 per cent of steam is bled from the turbine at a point between the ninth and tenth stages, and this steam is used for heating the condensate. The amount of mechanical work sacrificed is 10 per cent of the work possible with 1 per cent of steam, that is one-tenth of 1 per cent of the total mechanical work produced. The saving in the coal consumption by utilizing the heat losses of the alternator is accordingly only one-tenth of 1 per cent of the whole heat consumed by the power station, which is one-tenth only of that on which the author's figures of capital costs are based. There is another difficulty arising out of the use of condensate for cooling the alternator. The condensate temperature may vary, due to variation of the vacuum. In the case of a drop in the vacuum due, for instance, to decrease in the quantity of circulating water, the temperature of the condensate would drop suddenly, causing a rise in the temperature of the alternator. The output of the turbine may drop slightly, but not in proportion to the reduced capacity of the alternator, owing to the lower temperature of the cooling water. Another disadvantage of the proposed system is the fact that at the higher loads, when coldest water is desirable for cooling the alternator, the temperature of the condensate is highest, with the result that the overload capacity of the alternator is considerably reduced. It is of interest to compare the trend of development of turbo-alternators with the development in the cooling arrangements of turbo-compressors which has taken place during the last 10 years, and which is diagrammatically illustrated in Figs C, D and E. In 1910 turbo-compressors used to be cooled by water within the

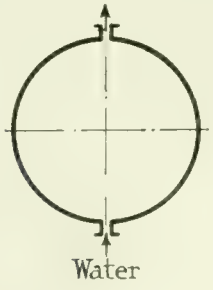


FIG. C

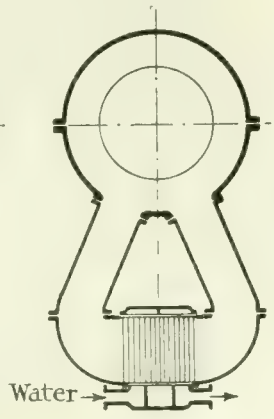


FIG. D.

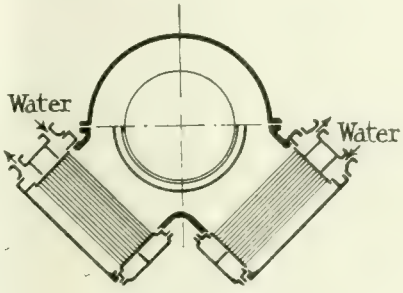


FIG. E.

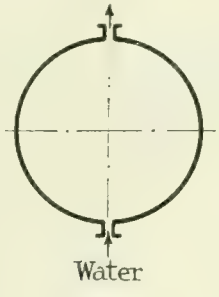


FIG. F.

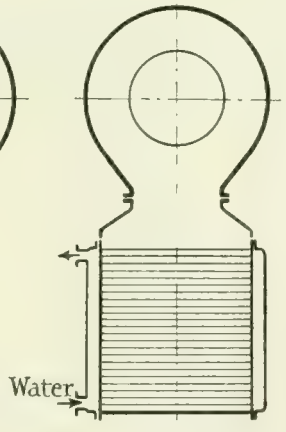


FIG. G.

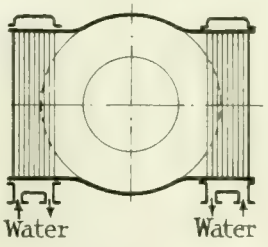


FIG. H.

compressor itself (Fig. C), and the air was cooled whilst it was being compressed. Owing to various disadvantages attached to this system a well-known firm developed a few years later a system of cooling (Fig. D) in which no cooling took place in the compressor itself, the whole of the air being taken at various stages to a separate cooler where all the cooling took place. In the latest designs (Fig. E) the same principle is retained, but the coolers are arranged within an extension of the compressor casing, the whole forming a compact unit. A similar development is likely to take place in connection with the proposals for cooling turbo-alternators, as is diagrammatically illustrated in Figs. F, G and H. In the author's proposals water is applied for cooling within the alternator itself (Fig. F). Recent developments are in favour of a closed air circulation with an air cooler (Fig. G.) arranged within air ducts close to the alternator itself. In a further development this cooler can be arranged within the alternator stator casting (Fig. H), the whole forming a compact unit. This arrangement would be particularly suitable for motors and generators for marine work. The space occupied is quite reasonable, as is shown by the sketches which are approximately to scale. Most of the disadvantages of present arrangements indicated by the author, such as excessive space required by the air ducts and risk of sea water reaching the winding, are eliminated.

Mr. J. Shepherd (*in reply*): Mr. Peck considers the suggestions for improvements very fairly and raises certain questions, some of which have been dealt with in my opening reply (see page 148). He suggests making the supporting fingers between the teeth of air-cooled machines of larger section to give a more solid core. This construction sacrifices ventilating space. The method of core support proposed in Fig. 10 allows the entire surface of the tooth to be supported, and the greater the support the better the cooling. Mr. Peck very correctly states that the two difficulties in the designs shown in Figs. 9, 10 and 11 are risk of water leakage and the application of insulation to the curved end connections. The first difficulty I have dealt with already. With open stator slots the stator bars and end connections can be insulated and steam pressed before insertion into the machine, leaving only the joints between top and bottom layers to be insulated in position. This portion of the insulation need not necessarily be clamped against the metal supports. The packing of the end turns correctly into place need not present any difficulties. Steam can be circulated through the coolers to heat up the coils and render the insulation pliable; in fact the supports can be used during construction in a similar manner to steam-heated moulding presses. Regarding the reliability of fusion welding, the repairs carried out to the engines and boilers of the German liners in New York Harbour during 1917 furnish an example of what is possible under far more difficult conditions than in a well-equipped works. Further, the designs of coolers can be modified to some extent to enable the simplest and most easily welded joints to be used. If a high-pressure marine cylinder broken to fragments can be repaired in situ by fusion welding, there should be no difficulty in successfully fusion-welding any designs put forward, under the more comfortable workshop conditions at Trafford Park, for example. Fusion welding has only been developed during the last 10 years, and progress during the last 5 years has been remarkable. Quite apart from the applications noted in the paper other branches of engineering, particularly shipbuilding, boiler work, pipework, are further developing fusion welding, and progress during the next few years will be even more remarkable. The practicability of building up a substantial metal seal to the water joints by deposition from an electrolyte under high velocity is also capable of practical development.

Professor Miles Walker briefly reviews existing proposals for the cooling of turbo-alternators by water; so far as I know I have recorded them all in my paper. No originality can be claimed for water cooling *per se*, but only in the character of its application. I have indicated the various weaknesses of air-cooled machines and shown how, by using water-cooling devices of suitable designs, these existing weaknesses may be remedied. It is the general opinion of experienced engineers that water cooling of alternators must come, and I endeavour to show how its adoption can be most usefully applied. Respecting suitable resistance metals, the most suitable appear to be copper-nickel alloys, but I do not krow of any with a resistance so high as 50 times that of copper. Monel metal is an alloy in commerce having suitable properties:

Melting point	2,490° F.
Electrical resistance	25 times that of copper
Tensile strength	88,000 lb. per sq. in.
Yield point	56,500 ,, ,,

In reply to the query of buying water-cooled alternators, I hope I may buy many such machines. With respect to the proposals not being complete, they are only intended as suggestions on which working designs may be based. The question of utilizing the internal heat from generators is dealt with later.

Mr. Sills criticizes the proposal of steel-tape bands. My objection to solid steel bands applies more particularly to those of special steels such as chrome and nickel, and not to ordinary carbon steel of which the rotor bodies are forged. Dealing with stator cores, future machines will generally be so large that building must take place on site where facilities for heating up during construction do not exist. The cooling elements may, however, be used as heaters if desired. The proposal of air spaces between the two layers of stator bars in the same slots appears to be a heavy sacrifice of useful and very expensive core space. Regarding hollow rotor teeth, the patent mentioned by Mr. Sills is British Patent No. 17,414/1908 covering a construction for hollow air-cooled teeth. Dealing with the proposal shown in Fig. 8 (*f*), if desired the closing strip may be caulked and welded, or dovetailed and welded; but welding alone offers a strong construction. Regarding water cooling displacing air cooling, there can be no question that large machines in future must be so constructed; the idea may be too novel for immediate acceptance.

Mr. Juhlin is a designer of very wide knowledge,

and I know has experienced most if not all the troubles set out in the paper. Whilst most of the mechanical weaknesses have been rectified in the latest machines, the mechanical weakness of the insulation still remains. I cannot consider Mr. Juhlin to be really serious when he questions the necessity of greater stability of the end turns. With practically every breakdown the end-turns and the ends of the stator bars are the first points examined when investigating the cause of the breakdown. The lives of insulation given in Fig. 7 are expressions of opinion and not fundamental laws. Other quantities are also involved besides temperature, viz. stiffness of the conductor, character of its supports, operating and transient voltages. These facts are clearly brought out in the paper to which Mr. Juhlin refers, viz. "Experimental Data Concerning the Safe Operating Temperature for Mica Armature-Coil Insulation," by F. D. Newbury (*Transactions of the American Institute of Electrical Engineers*, 1915, vol. 34, p. 2747). He showed that the original Niagara machines with solid conductors (1 11/32 in. × 7/16 in.) had a life of 20 years with a working temperature of over 300° F. During that time only 4 per cent of the stator bars were replaced, although the reactance was only about 5 per cent. Later Niagara machines were built with weaker bars, which failed very quickly owing to the lack of rigidity and the consequent bending of the bars where leaving the stator slots. Mr. Juhlin points to the great strength of mica under compression. Unfortunately, with thoroughly laminated bars the mica insulation is usually stressed as a beam, more or less supported at intervals. Now if the bars and connections throughout their entire length are contained in continuous winding slots the insulation can only be subjected to compression stresses, the condition of maximum strength. The difficulty of tight packing of end turns together and against their driving projections is raised. With open stator slots the coils and end connections can be insulated and steam pressed before winding, the bottom layer can be inserted with temporary (split) projections between the groups of end connections, and the whole gradually steam heated. When the insulation is pliable and soft the split temporary projections can be gradually opened by tapered screws, and the groups of conductors tightly clamped together and one by one the permanent projections inserted. The cooling devices when steam heated allow greater winding facilities than in the case of the ordinary machine, and I cannot see any difficulty in making a compact mechanical structure of the end turns. The question of expansion has already been dealt with; the increment in length is so small that allowance for it can easily be given. The rotor construction shown on the slide to which Mr. Juhlin objected was one from his own firm, taken some little time ago.

Mr. Lamb raises the question of waste-heat value, which is dealt with later. I am glad to learn his experience of failures has been limited in extent. Regarding reliability of low-speed turbo-generators, I referred of course to like conditions and not to cotton-insulated low-speed plant against mica-insulated turbo-generators. In confirmation of my opinion he should see Mr. Newbury's paper mentioned earlier.

Mr. Ratcliff discusses reactances: the matter, however, is rather wide of the subject of the paper. With the large systems of the future, with single stations exceeding 200,000 k.v.a., external reactances will probably be a necessity. The form that will be adopted will be something different from present designs, as perfect mechanical strength must be their first necessity.

Mr. Kuyser considers water cooling only from one point of view, viz. heat transference. The necessity of mechanical support to the windings is an equally important matter, especially with the large machines of the future. Regarding water pressure in the rotors with speeds of 3,000 r.p.m., this will be considerable in amount, though much under the pressures of ordinary hydraulic practice. For a pressure of 1,000 lb. per square inch a small steel pipe would usually be about 0·125 in. thickness. The thickness shown in Fig. 8 (*f*) is about 1 inch. If desired the closing plug may be dovetailed. The centrifugal stress is only about 600 lb. per lineal inch. Leakage at the supports at each end of the rotor can be prevented by suitable packing compressed to a higher degree than the internal water pressure, and each fixing nut if necessary can be augmented by a ring of set screws. The design of fibre cage supporting the ends of the stator bars as they leave the slots, proposed by Mr. Kuyser, may appeal to the designer, but it cannot be placed in position on groups of bars without some slack, and at the best is a more imperfect support than the continuous slot. The external air cooler removes the difficulty of air filtration, but leaves the alternator with its present weaknesses, nor does it entirely remove the fire risk. The example of temperature distribution given by Mr. Kuyser shows a maximum variation of 12 degrees C. When some of the air passages are partially choked by dirt a larger difference may be expected.

Mr. Baumann deals with the heat value of the alternator losses, and with a figure of £17,000 given verbally at the Manchester meeting. With an electrical unit of 10,000 kw. and 5 per cent loss, 50 per cent load factor, and coal at 50s. per ton, the heat given to the hotwell by the circulating arrangement shown in Fig. 13 is equivalent to that of 300 tons of coal per annum, which capitalized at 6 per cent for 15 years =£17,000. In stations having no exhaust steam and where the hotwells are heated by live steam this is the correct figure. If, however, exhaust steam is available by bleeding the exhaust steam, or by fixing a heater near the exhaust end of the turbine, the same amount of heat can be obtained at a much cheaper rate. Many existing stations are still using live steam for heating. Regarding the form of air cooler proposed for marine use shown in diagram form (Fig. H), the arrangement is certainly very compact and I have been wondering whether it has the approval of Mr. Baumann's colleague, Mr. Peck. He views with considerable misgiving the presence of solidly welded water joints inside the machine, but the arrangement shown in Fig. H will contain many more water joints either packed or expanded. The rolling of the ship in rough weather will throw considerable racking stresses on the long vertical air cooling tubes, and consequently upon their joints at the tube plates.

Removing the coolers further from the alternator gives no benefit, as the current of cooling air would immediately sweep the leakage water into the windings. In effect, what Mr. Baumann suggests is a cooler with metal cooling tubes about No. 18 gauge, whilst in the proposals put forward metal of less than No. 10 gauge would not be used, and generally the enclosing walls would be $\frac{3}{8}$ inch or more in thickness. With an external cooler for the ventilating air it would appear that, whilst the alternator would remain with its present weaknesses, the risks of water leakage would be certainly as great with the external coolers (Fig. H) as with the internal coolers (Figs. 9 and 10). The moral to be drawn is that a novel construction (Figs. 9 and 10) is open to suspicion whilst a familiar construction (Fig. H) is not. If water cooling is contemplated at all the problem should be viewed broadly and all its possible advantages considered.

North-Eastern Centre, at Newcastle, 26 January, 1920.

Mr. J. Rosen : I cannot agree with the author that turbo-alternators as at present designed are unreliable. Machines put into commission 15 years ago are still running, and during this period have received only occasional overhauls. Certainly there have been difficulties and failures, but these, as pointed out in the paper, are largely the result of the large increases in the size of plant, and also due to station conditions ; the several causes of the troubles have now been traced and overcome. Station engineers, as a rule, do not pay sufficient attention to the electrical end of the plant. If on every occasion when the turbine is overhauled—about once a year—the alternator rotor were removed, an examination made of the alternator windings, and the stator windings subjected to a pressure 50 per cent above phase voltage, a large number of the serious breakdowns would, I think, be obviated. A local breakdown under the pressure test is readily repaired, whereas a breakdown on load is more serious and usually results in the complete rewinding, and even rebuilding, of the stator core with consequent inconvenience and expense. An examination and test such as those outlined can be made at a time when it is possible to spare the machine and make the necessary repairs. Such an overhaul is well worth while, and is an effective insurance against a breakdown at a time when the machine can ill be spared. I shall now refer briefly to some of the difficulties mentioned in the paper. The critical speeds and stresses in the present design of rotors are now accurately calculated. The running speed is kept well away from the critical speed, and also a large factor of safety for the stresses is allowed in the design. Recent improvements in material, and new methods of testing, reduce to a minimum the danger of a breakdown due to faulty material. The author refers to a 36 in. diameter rotor running at 3,000 r.p.m., which gives a peripheral speed of 470 feet per second. This speed certainly appears to be high, and I should be interested to have any further particulars of this machine which the author is able to give. Nickel chrome steel rings are not a novelty, as the author suggests. They have been successfully employed by Messrs. C. A. Parsons & Co. during the past 10 years. Also, quite recently, a design of bronze rotor end cap filled with high-tensile steel bands has been used ; this cap was fitted to a single-phase alternator, the rotor windings of which were secured by the bronze end cap, as it was impossible to use nickel chrome steel rings owing to the resulting overheating due to eddy currents. Side slip of the rotor windings, mentioned on page 127, is eliminated by the accurate forming of the rotor coils and by suitably packing them. Exception is taken to the flexible coupling. This type of coupling with flat faces is perfectly satisfactory, so long as the working pressure is kept within limits dictated by long experience and the lubrication is properly arranged. An imperfectly lubricated coupling will certainly give trouble. A safeguard in case of fire is the use of steam sprays, which have been fitted inside the stator end-shields on a few machines in this country, but up to the present it had not been found necessary to use them. Another difficulty to which the author does not refer is the danger of grit, coke dust, or similar material being drawn into the alternator and thrown out by the rotor. The result is a sand-blast action on the stator conductors, which rapidly cuts into the insulation. I have had experience of such trouble, but before a breakdown occurred the fault was located. However, if a breakdown had occurred, the evidence of the cause of the breakdown would have been completely destroyed. This confirms the necessity previously mentioned for having periodic overhauls of the alternator. The author has encountered difficulties with what he terms " crushed strand " construction of conductors. I should like to say that cables made upon Parsons' cable-making machine have been very successful and have given little or no trouble. The special feature of the machine is that the cable is made of any desired section, and is formed without any cores and without crushing. The only pressure to be applied is that required for moulding the insulation on the conductor. By the methods employed, a very mechanical and substantial construction is obtained. Sweated joints with this type of conductor, with the strands stemmed tightly in the loop of the end-connection strip, give no trouble. The Haefley wrapping referred to on page 128 gives a very hard tube which has a high dielectric strength. The mechanical properties of such insulation, however, are not unlike those of porcelain, and it has proved in many cases unsuitable for use in turbo-alternators. Experience has proved that the insulation used must have flexibility, and must permit of relative movement between the copper and the insulation and between the various layers of insulation. Such flexibility is essential on turbo-alternators owing to the comparatively long length of conductor bar, as repeated expansion and contraction of the copper must take place while on load ; further, some " give " of the windings is inevitable when machines are subjected to short-circuiting such as is certain to occur in practice. The insulation and varnish chosen must be such that they always retain

this quality of flexibility. I recall a case of a breakdown under pressure test, at cracks in the hard insulation of a conductor bar, immediately after the machine had been dried out. A similar breakdown occurred on another machine due to the same cause after the machine had been in commission for four years. The author refers at length to the water-cooling of turbo-alternators, and he considers that it will eventually prove a cure for the difficulties experienced with the air-cooled machine. It might be of interest to give a short history of the earliest experiments in liquid-cooling, which I think was first applied to electrical machinery by Sir Charles Parsons in his first very high-speed dynamos built in 1884 to 1889. In these machines the shaft of the dynamo armature was hollow, and cool oil was continuously pumped through it to the outboard bearing. In 1904–5 an alternator was built in which the stator core was cooled by an arrangement of ducts very similar to those described by the author in Fig. 10. In 1905 another alternator was built in which the stator core was cooled by a series of longitudinal water pipes, which passed through specially provided tunnels towards the outside of the core and connected by water boxes at each end of the core. The results of the tests, as far as I know, were not published, but the experiments show that water cooling of electrical plant has already been seriously considered. With a water-cooled alternator there is the danger of bringing the water into proximity to the alternator windings and of possible leaks occurring. Leaks cannot be entirely obviated. In the case of the more recent water-cooled rotors of Messrs. C. A. Parsons & Co.'s manufacture referred to in the paper, weldless steel tubes are used to circulate the water and all the joints are made outside the stator end shields, so that if a leak occurs it is at once apparent and there is no danger to the windings. Facilities are provided for cleaning the water spaces. Designs with projections from the rotor body between the coil ends were set out, but were not adopted owing to the difficulty in making allowance for the expansion of the windings. It should not be forgotten that by bringing the stator end-windings throughout their length into close contact with metal, thicker insulation must be used, and therefore an increased heat drop must be allowed across the insulation, which means either more expensive machinery, or higher temperatures than are at present permissible; also there will be an increased eddy-current loss in the metal supports, and this loss will be by no means negligible. The paper gives engineers an insight into some of the difficulties with which the manufacturer has to contend, and I hope it will result in a better understanding between the station engineer and the maker, as it is only by the closest co-operation that difficulties can be foreseen and overcome.

Mr. W. G. Turner: I am most interested in the proposal to substitute water cooling for air cooling of turbo-alternators, which method I feel sure will be adopted extensively in the future. By the adoption of the method suggested of utilizing the condensate for cooling purposes the greater part of the heat losses of the alternator will be utilized and the plant be rendered more efficient. Further, a greater output and a more flexible alternator will be obtained from the same total weight of the material. The chief difficulty appears to be to design a machine in which the cooling water can be conveyed through the water-circulating system without leakage. Again a difficulty arises in that the condensate of the steam turbine does not always comply with the ideal conditions recommended. Firstly, plant has often to be run for a considerable time with leaky condenser tubes both before and after the discovery is made; secondly, there is the possible danger of impurities reaching the condenser through the priming of boilers; and, thirdly, with mixed-pressure or exhaust-steam turbines thick oil is always found in the exhaust steam and condensate in spite of precautions taken to eliminate it. These troubles would each tend to make the condensate impure and might cause corrosion or deposit. It would appear to be necesary so to design the machine that access could be gained to all water passages for cleaning purposes. Further, the water passages should be so designed and constructed as to prevent sudden changes in the direction of flow of the water such as would occur in the small pipes leading into the hollow rotor teeth, shown in Fig. 9, where the scouring action set up due to the change in direction of flow might ultimately wash through the metal and so cause leakage. These remarks should not in any sense be considered of a condemnatory character but as a means of drawing attention to possible causes of failure of the scheme now put forward.

Mr. J. W. Jackson: The author referred to the turbine as having been first installed in 1903, but I would point out that the turbine had become a commercial proposition on the North-East Coast some years before that date. In this district many experiments have been made on air cooling and filtering. Great difficulties had been met with on cloth filters and also on spray filters. The cloth filter from many points of view was very satisfactory while in use, but proved most difficult to clean when out of action, the particular difficulty being that of finding a laundry to undertake work of this sort, with which the usual power station staff appeared unable to cope. While reports as to the behaviour of the spray filter indicate great divergence of opinion, in some cases it has been found extremely sensitive to changes in humidity of the atmosphere, thus allowing large quantities of free water to enter the alternator system. The same trouble apparently can be caused by having too big a pressure or too small a pressure on the sprays; that is to say, there is an ideal pressure for the sprays in their original condition of cleanliness, and this pressure of course varies as the spray orifices become fouled. There is a further difficulty of keeping the spray system in order through severe frosts. We have, however, had experience also with the Heenan & Froude type of filter and have found a considerable degree of freedom from the troubles above mentioned. This, however, we consider to be due to the fact that we are continuously changing the water in the tanks, thereby keeping down to a minimum the solids in suspension and the concentration of solids in solution. A scheme has been developed for water cooling the circulating air on the inverse principle of the air heater. Circulating water such as is used in the condenser would prove quite suitable for this work.

As the air is contained in a completely closed system it requires cooling only, and so no filteration troubles can possibly develop. The author has developed a system of water cooling which will call for a wider application of this system and which has already been put into practice, so far as the cooling of the rotor windings, with very good results. The author points out the necessity for providing against the possibility of corrosion and for making sure that the water employed will be quite inert. There are two special difficulties that appeal to us in this particular respect. One is that it would be far better to use water which is entirely separated from the condensate but which can be cooled in a standard water cooler, using the condensate as the circulating water for this cooling system. The water used on the enclosed system will then only need to be treated once to remove all corrosive influences, and experience has proved that with suitable chemicals the water can be kept in a perfectly neutral condition from a corrosion point of view. If, however, the condenser condensate water is used direct on this system, then the whole of the water passing through the alternator will require treatment, and this we are afraid will condemn the system since, in order to put this cooling water into such a state that there will be no danger from corrosion, the water may just as easily be rendered totally unsuitable for boiler-feed purposes. The other difficulty is to ensure that the water used on the cooling system is never allowed to fall in temperature below the dew point, as otherwise a serious amount of free water would collect on the surfaces of the whole of the cooling system and considerable damage be done to the alternator. On page 131 the author points out difficulties experienced with rotor couplings of the flexible type. We have seen many turbo-generators of various capacities fitted with flexible couplings and the conclusion we have arrived at is that, provided the wearing surfaces are kept under observation when the remainder of the plant is undergoing its general overhaul, so as to make sure that the couplings really are flexible and do not become rigid, it is by far the best system of connection between the two different types of machines. We have seen very serious trouble develop on turbo-alternators where the couplings have been rigid, and the cause for this does not seem far to seek, namely, that unless the designer has laid the plant out in such a way that the centres of the respective machines are in line when the turbine is working under a certain loading condition which will be normal load, there is bound to be trouble from vibration due to the differences in height of centres on the no-load and light-load conditions which may cause this vibration to persist for even two hours after the machine has been got on to full load. It will be seen that the point that the designer must keep before him in this connection is an extremely difficult one to settle, and so we favour the flexible coupling every time for this reason. The author points out the necessity of obtaining a varnish or compound for treating the coils of his alternator which will have the following properties: good heat conductivity, high insulating properties, water-proofing properties, and be fire-resisting. Should the author be successful in his search we should be glad to hear further from him.

Mr. J. R. P. Lunn: I can fully confirm what Mr. Jackson has said with regard to the corrosive action of condensed water, as I know of cases where whole lengths of wrought-iron feed pipes have had to be renewed owing to the extent to which they were corroded by the condensed water passing through them. I should like to ask the author whether oil could not be used for cooling purposes instead of water, as with oil a leakage would not be so likely to cause trouble. The oil would of course have to be cooled and that would tend to increase the cost. I can also confirm from my own experience what the author has said in regard to the choking up of the air passages unless great care is taken in filtering the air. Cloth filters are very expensive and troublesome to keep in good working order, and they are liable to get choked with dirt and to reduce to a serious extent the air passing through the alternator. We are using wet air filters of the water-film type and find that they give satisfactory results. They do not remove the very fine soot from the air, and if white cotton wool is suspended between the filter and the alternator it soon becomes dirty, but we find very little dirt in the alternators, and that is the main consideration. I had a case recently of the cracking of the micanite insulation on the stator bars under the short-circuit conditions referred to by the author. An internal short-circuit, set up by arcing at a defective joint, occurred in a 3,000 kw. alternator, and although the machine, which is protected by balanced transformer trip-gear, was disconnected before any appreciable damage was done by the arc, it was found that the micanite insulation on all the stator bars of a certain length was cracked at the point where the bars emerged from the core plates. These stator bars were unsupported except by the end connections as they did not project very far, but other stator bars which projected much further from the stator core were provided with supports and these bars were not injured by the strain set up by the short-circuit. The very trifling amount of burning or fusing which occurred in this case indicates, I think, the great advantage of efficient protective gear, and especially of the system of killing the alternator field at the same time as the main switch is opened. In order further to minimize the damage caused by an electrical breakdown in an alternator, I consider it desirable to fit dampers in the air ducts, so that whenever there is reason to suspect that firing is occurring inside the alternator the damper can be closed and the supply of air shut off. I have fitted dampers to my alternators but so far have not had reason to use them. I do not understand why there should be so much difficulty in measuring the temperature of the alternator windings while the machine is running. It is surely possible to fix a distance thermometer at some point in the alternator at which a temperature very nearly approaching the maximum will be attained, and although it may not be possible actually to measure the maximum temperature it should not be difficult to obtain data which would enable the maximum temperature to be calculated with approximate accuracy from the readings of this thermometer. At any rate this would be a much more accurate guide than to take the temperature of the ventilating air leaving the machine, as when the ventilating passages become choked the

temperature of the air leaving the machine for any given conditions of loading would be lower, and the actual temperature of the windings would be higher than when the ventilating passages were clean.

Mr. C. T. S. Arnett (*communicated*): There is undoubtedly much to be desired in the quality and method of insulating the stator windings of large alternators; also the end bracing of some machines is far from satisfactory, especially in alternators of 6,000 kw. and over. I consider that an alternator wound for 3,000 volts and direct coupled to the supply, i.e. not through transformers, has to stand surges which make it necessary to insulate this machine with as heavy insulation material as that used for, say, a 10,000-volt machine, since the 6,000-volt machine may quite well have to stand voltages on a surge of a very high value. Amongst other machines we installed a 6,000 kw. set at 2,500 volts, and after this machine had been running six months with an unearthed neutral one of our high-tension overhead feeders went to earth on one phase, a short-circuit occurred, since there had evidently been a weak spot in the windings of the alternator on one other phase which did not show until the disturbance on the overhead feeder fault developed, the end windings were very badly distorted, and the machine had to have these end connections rebuilt. The contractors were inclined to blame the wet air filter. The machine was put on load again after repairs had been effected, and the wet air filter was kept out of commission, the insulation then varied to a certain extent with the humidity of the atmosphere but gradually fell to the dangerously low figure of 0·4 megohm. The machine was taken out, cleaned, varnished, and special attention was given to a point where two phases cross at the end windings, then put back into commission with the wet air filter in commission and up to the present the insulation has remained good. Dampers are now fitted to the wet air filter and the air outlet. If these are not closed when the machine is standing, condensation takes place on the winding and the chimney-draught action of the ventilating passages to and from the machine conducts outside air and dust to the windings, and if the atmosphere is very humid condensation takes place. It is therefore in my experience absolutely essential to have dampers to stop natural draught circulation of air when a machine is cold and the wet air filter is off. All this goes to show that in this case it is not the wet air filter (if properly used) that develops weak spots in the insulation but the circulation of moist air and dust from outside. Tests indicated a fall of insulation resistance when dampers were left open and the wet air filter was off on humid days with the machine standing or running, whereas on all occasions insulation resistance increased when dampers were closed with the machine standing, and remained constant when the machine was running on the wet air filter. There is no doubt that the proper specification and proper handling of quotations by the buyer plays a great part in the satisfactory service of an alternator. It is too often found in a large works, such as an iron and steel works, that an alternator is bought on price by the chief mechanical engineer who has no knowledge of electrical engineering, and the sooner general managers recognize that the chief engineer must be both an electrical and a mechanical man the sooner will they get more continuous service from their rapidly increasing electrical equipment. Makers should be encouraged to vie with each other from the point of construction rather than of price, although price must be taken into consideration but only when balanced against construction. To do this with all electrical equipment will require men of a high standard which I am sure can be obtained from our university graduates who must also have had years of practical experience. There is much to be said in favour of the re-circulation of the discharge air of the alternator, after passing this air through a cooler. This is, in my opinion, the best method for very dirty atmospheres.

Mr. T. Carter (*communicated*): I think that on the whole the paper is much too pessimistic, and one of the most definite answers to the rather gloomy position taken up by the author is that such accidents as he has described do not happen daily. I think that manufacturers are fully aware of the defects which are bound up with their designs, and they are already working very satisfactorily along the lines of many of the remedies proposed by the author. We are all waiting patiently for someone to discover the perfect insulation, the characteristics of which are well known but so difficult to produce. I hope that the discussion on this paper will be an indication to the Electrical Research Committee that the problem of insulation is extremely urgent.

Mr. H. W. Clothier (*communicated*): It is over 20 years since Ferranti single-phase alternators with stationary armatures were made, and, if I remember correctly, the end windings of each core section were closely packed in a separate cast gunmetal box lined on the inside with moulded ebonite. This box formed a support for the coil and was a system of metal-clad protection for the conductors. At the same time it clamped the end core-plates. It seems to me that the armouring of conductors, so usefully applied to other apparatus on a power-supply system, should be equally beneficial to alternator design, and that the practice initiated on the early British alternators and advocated by the author should have every encouragement from alternator designers. On reference to Fig. 10 a weak point occurs where the coil leaves the core. It is unarmoured here and I understood the author to say that the particular place was a source of trouble on existing designs. It will be interesting to watch the future development. If it leads to a complete armouring of all conductors throughout the whole electrical circuit, such a policy certainly seems to make for strength and safety.

Mr. W. T. Dalton (*communicated*): Whether station engineers agree with or dispute the author's statement "that modern turbo plant does not compare favourably for reliability with the old low-speed reciprocating sets," will probably depend upon individual experience. The author states that failures as a rule only occur on large sets; but 2,000-kw. to 3,000-kw. generators would not be called large as matters progress to-day, and there have been failures with such sizes. In two instances the machines were running at unity power factor with the air outlet temperature 90 to 95° F.

This does not look like temperature trouble, but rather failure of insulation. The present general design of alternators makes it necessary to arrange the end windings of the stator in a confined space at each end, the space available being determined by the diameter of the stator frame; but even at the sacrifice of symmetrical design more room could be given for the end windings by increasing the diameter at each end, thereby providing greater space for insulation, air-cooling, and efficient anchoring. In comparing old plant with modern plant one must take into consideration that the present-day ideas of rating are very different from those of years ago; and this fact, together with the high speeds which are now universal, must tend towards greater risk. Vibration on such plant cannot be entirely eliminated, and therefore the opening up of plant for frequent inspection will in many cases result in the detection of small defects which, if allowed to develop, would lead to complete breakdown. It is possible for a dry air filter to be cleaned by a vacuum cleaner while the machine is running, and this practice is in common use. The fitting of a breaking switch in the main alternator field operated in conjunction with the Merz-Price protection gear has come into favour of late years, and prevents the disastrous fusing of the core and conductors in the event of an internal short-circuit. Apart from more complete periodical tests of the protection gear, this switch should be operated by hand just previous to each occasion when the machine is put on load, in order to make as certain as possible that it is free to operate at a critical moment. Certain designs are liable, if not carefully adjusted, to remain fixed in the closed position. Where step-up transformers form part of a turbo-alternator unit, the voltage of the alternator should be chosen as low as is compatible with other considerations of design so as to throw the greater risk on the transformer, which from its character has a greater factor of safety. Transformers so used with a certain amount of reactance will act as a buffer in case of failure of the alternator. It cannot be disputed that to add reactance to an alternator adversely affects the regulation of the machine, but this would not be so if the ordinary commercial power load did not produce a lagging power factor on the system. As the size of generators increases it becomes more necessary to limit the enormous energy given out on a short-circuit, and as with our present knowledge reactances are the most efficient method of limiting this energy, the objection to their use in so far as it affects the regulation of the alternators would disappear to a very large extent on a unity-power-factor system. This is another reason why the whole question of the design and use of efficient power-factor correction apparatus should receive serious attention. On a fault taking place on one alternator, external reactances, fitted to a group of alternators in the phase leads of each, limit the current given out by the remaining plant, partly by the combined effect of the reactances on the good machines and the reactance of the faulty machine; but the faulty machine has no reactance protection if the stator fails at the machine side of the terminals. To relieve the mechanical stress set up on the faulty machine, reactance could be inserted in each phase winding at the star point. Whether external reactance should be introduced partly at the phase leads and partly in each winding at the star point is a matter that would require careful consideration. Certainly it might be argued that it is better to give as much protection as possible to the good plant left running and let the faulty set take its chance. If this argument be maintained, no reactance should be inserted at the star point.

Mr. J. Shepherd (*in reply*): Mr. Rosen, speaking as a designer, does not agree that turbo-alternators as at present constructed are unreliable; obviously a standard of reliability is wanted. Mr. Rosen states that machines have been in commission for 15 years with only occasional overhauls. If that standard were met by all turbo-alternators I would agree that turbo-alternators are thoroughly reliable, but it is common knowledge amongst engineers that, whilst a few isolated machines may show so excellent a record, the case is not representative. I agree with Mr. Rosen regarding the necessity of periodic and thorough overhaul, which of late years has been impossible to carry out owing to lack of spare plant. The breakdown from sandblast action of grit I have not experienced or seen; an efficient filter would prevent the trouble. I note with interest the description of rotor cooling by water, designed by Messrs. Parsons, using weldless tubes expanded in, also a brief account of earlier experiments. The eddy-current losses in the coil supports cannot be calculated, but a superior limit can be defined which is of trifling amount.

Mr. Turner gives his views on the unsuitability of the condensate for general cooling. I understand that in the Newcastle district the condensate is found to be corrosive. In such cases a closed system with auxiliary coolers would be necessary in place of the arrangement shown in Fig. 13. The water passages in Fig. 9 must be taken only as diagrammatic.

Mr. Jackson's remarks are of much value coming from an operating engineer having had experience with water-cooled turbo-generators. I understand that experience at Carville points to the necessity of a closed cooling system owing to the corrosive nature of the condensate. The risk of surface condensation is fully dealt with in the paper. Regarding flexible or rigid couplings, the general experience is that rigid couplings give less trouble than flexible couplings and most makers only supply them when specially ordered.

Mr. Lunn also deals with corrosive condensate. The problem certainly appears to be acute in the Newcastle district. The possibility of oil cooling is dealt with elsewhere.

Mr. Arnett recommends external air coolers. I have dealt with this proposal fully in the Manchester discussion (see page 272), to which I would refer him.

Mr. Clothier asks regarding supports to the stator coils on leaving the core slots. Although no support is shown in the small scale drawing (Fig. 11), the profile of the stator tooth is carried on the end supports and gradually cut away as the stator bars of the same group converge into their common winding slot.

The remarks of the other contributors to the discussion do not call for specific comment as the points they raise have already been dealt with.

EDDY CURRENTS IN STATOR WINDINGS.

By H. W. Taylor, Associate Member.

(*Paper first received* 30 *January, and in final form* 16 *September*, 1919; *read before the* South Midland Centre, *at Birmingham*, 7 *January*, 1920.)

Introduction.

The problem of the elimination of eddy currents from the stator conductors is one of considerable importance in the design of present-day alternating-current machinery, and the original memoir of A. B. Field on this subject, published in the *Transactions* of the American Institute of Electrical Engineers, vol. 24, in 1905, has been of inestimable value to designers.*

Field's paper contained, in the first place, a general physical discussion of the problem, and concluded with an analytical investigation of some of the usual cases which arise in practice. The analytical treatment of the subject gives rise to the differential equation $\frac{d^2y}{dx^2} = K\frac{dy}{dt}$, but to those who are not familiar with it, or who are not skilled in the manipulation of its solution, a full appreciation of the relations of magnitude and phases of currents in the various parts of a conductor or a system of laminated conductors must be difficult.

In the present communication, therefore, it is proposed to attack the problem in a synthetic rather than in an analytical manner, with a view more especially to dealing with some of the more advanced problems which have demanded consideration during recent years. The author appreciates that the possibility of such a synthetic treatment is evident from the early part of Field's original paper, but he feels that a development of this subject on these lines is of considerable value, especially as it leads to an approximation which considerably simplifies the calculation of most practical cases.

The subject matter of the paper is divided under the following headings:—

(1) General physical discussion and calculations of a bottom conductor in a slot.
(2) Calculation of a conductor higher in the slot than the bottom.
(3) Depth of conductor for minimum loss and minimum temperature rise.
(4) Losses in top conductors when subjected to the external influence of currents out of phase with those they themselves carry (as in some conductors of a two-layer fractional-pitch winding).
(5) Losses in conductors consisting of a number of laminations connected solidly together at the ends.
(6) Losses in coils in which insulated laminations are continued from turn to turn.
(7) Losses in conductors and coils in which insulated laminations successively occupy different positions in the conductor.

* Also see M. B. Field, *Journal I.E.E.* 1906, vol. 37, p. 83.

Two appendixes are added dealing with special features of the problem, viz.—

I. Complete synthetical treatment of the eddy-current problem in solid conductors.
II. Losses in conductors of such irregular shapes as are not amenable to mathematical representations.

List of Symbols.

a = ratio of total width of copper across slot to width of slot = (w/y).

b = ratio of core length to half length of one turn of winding.

c = ratio of total depth of copper in a laminated conductor to total depth of copper, i.e. including all insulation between the laminations.

d = a quantity involving the various factors in the eddy-current calculations and equal to $2\pi H\sqrt{(fa/10^9\rho)}$ or $\frac{1}{3}H''\sqrt{(fa)}$ for copper at 100° C.

f = frequency in periods per second.

g = a quantity involving certain of the factors in eddy-current calculation and equal to $4\pi^2 fa/10^9$.

h = height of a conductor in cm. considered as a variable, measured from the bottom of the conductor.

H = total height of a conductor in cm.

H'' = total height of a conductor in inches.

j = mathematically the imaginary quantity $\sqrt{(-1)}$, physically the indication of a time lag of a quarter of a complete period.

K = in general the extra loss factor, i.e. the ratio of the extra loss with alternating current to the normal loss with direct current.

K_1, K_2, etc. = extra loss factor due to local eddy currents in portions of a laminated conductor.

K_0 = extra loss factor due to circulating eddy currents in a laminated conductor.

m = number of turns in a coil, or in a two-layer winding the number of conductors per slot in each layer.

m, in Appendix I, is a quantity involving certain of the factors in eddy-current calculations and equal to $2\pi\sqrt{\left(\frac{fa}{\rho \times 10^9}\right)}$.

n = number of laminations in a laminated conductor.

N = number of laminations in an equivalent laminated conductor.

p = in general, the number of the conductor under consideration counting from the bottom of the slot; and in particular, the total number of conductors in a slot.

P = equivalent conductor for any particular arrangement of conductors.

q = in general, the number of any particular lamination of a conductor counting from the bottom of the slot or from the bottom of a particular conductor, as the case may be.

r_1, r_2, r_3, etc = fractional portions of an unevenly divided conductor.

r = in the case of a conductor divided into two unequal parts, the fractional part that the upper section bears to the whole depth; in cable conductors the fractional portion of a cycle of transference which is completed; and in step-by-step transference, the number of laminations which have been transferred when the winding is completed.

s = fractional number of coils in relation to the total number in the winding, the top sides of which are subjected to external influence out of phase with their own current.

t = a particular conductor in the top layer of a two-layer conductor.

w = total width of copper across slot, cm. or inches.

y = width of slot, cm. or inches.

ρ = specific resistance in practical units, ohms per cm. cube.

ϕ = in windings with fractional pitches the phase difference between currents in the top and bottom layers in those slots having conductors belonging to different phases.

(1) General Physical Considerations and the Calculation of a Bottom Conductor in a Slot.

General considerations.—Eddy-current phenomena arise from the fact that when a conductor carries current, flux passes not only around the conductor as a whole, but also along paths situated either wholly or partially inside the conductor itself. The result is that whereas direct current would be evenly distributed over the whole of the section, with alternating current there is a different virtual value of current and also a different phase of current for every symmetrical lamina in the conductor.

When a conductor is situated in the usual slot with parallel sides, the local fluxes pass normally across the conductor and complete their circuit by traversing the iron at the back of the slot. The reluctance of this portion of the path is considered to be negligible.

The investigation of eddy-current phenomena is carried out in the four following stages, in each of which one of the fundamental laws or relations of electromagnetism is applied. The stages are enumerated specially with reference to a bottom slot conductor as follows:—

(1) The total current between any lamina and the bottom of the slot produces an alternating magnetomotive force, the quantities being connected by the usual $4\pi/10$.

(2) This alternating magnetomotive force gives rise to alternating flux density across the lamina. These quantities are connected by the magnetic reluctance of the path pursued by the flux passing through the lamina in question.

(3) The total alternating flux between the bottom of the conductor and the lamina in question produces an alternating electromotive force between these two points normal to the section. The relation between these two quantities involves the frequency and also, if the pressure is expressed in volts, the relation between the absolute and the practical unit of voltage.

(4) This electromotive force combined with the resistance component of the applied external electromotive force gives rise to a current in the lamina in question. The value of this current is governed by the resistance of the material.

In the usual analytical investigation a symbol is taken to represent the complex current distribution in the conductor, and after operating upon the symbol in accordance with each of the physical relations enumerated above, the result is equated to the original symbol, thus forming a differential equation. The differential equation may, however, only represent in general terms the conditions of any particular problem, or, in other words, the same equation may be representative of several allied problems, so that its solution only discloses in general details the nature of the current distribution as represented by the symbol. The exact details are subsequently determined from a knowledge of the distinctive features of the problem in hand.

In the proposed synthetical treatment, instead of basing the argument on a symbol which we conceive to represent the final complex distribution of current in the conductor, we start by assuming the distribution of current to be uniform, as would be the case if the external electromotive force were the only one under consideration.

We then proceed to determine the simple algebraical expressions for the physical quantities which, in turn, would result from this uniformly distributed alternative current. We are thus able to calculate a local current in the conductor, which we can conceive is superimposed upon the original current in order to satisfy the alternating flux set up by the original current. This alternating current, whatever its actual value in any lamina, is everywhere 90° out of phase in time with the original current.

We may next proceed to take the eddy current thus found, which we will call the eddy current of the first order, and carry through the same processes as were applied to the original uniformly distributed alternating current, and we shall then obtain what we may call the eddy current of the second order which will flow in order to satisfy the alternating flux set up by the eddy current of the first order.

This second eddy current will, in turn, be 90° in time phase behind the first eddy current; that is, it will be in exactly opposite phase to the original uniformly distributed current.

In the same way we may go on indefinitely calculating successive orders of eddy currents, each of which will lag behind the previous one by 90°.

When we have carried our calculations to a sufficient extent it will be found that the total resulting current is the same as that obtained by the analytical method. The value of the present method lies in the fortunate fact that for most practical cases it is only necessary to calculate the eddy current of the first order; for it is found that if conductors are so deep that the second order is appreciable in magnitude, the total loss in such conductor is too high to admit of it being of practical use.

Calculation of bottom conductor.—We will now give the simple mathematics for the proposed method as applied to the simplest case, viz. that for the bottom conductor in a slot. The process is indicated graphically in Fig. 1.

Starting with a uniformly distributed alternating current of 1 ampere per sq. cm. (see Fig. 1*a*), the total volume

of current between the bottom of the conductor and any point at distance h from the bottom is $h\,w$.

The magnetizing force at $h = 4\pi w h/10$ (see Fig 1*b*), and the flux density at $h = 4\pi w h/10\ y = 4\pi a h/10$.

The total flux linkage between h and the bottom of the conductor is

$$4\pi a/10 \int h\,d\,h = 2\pi a h^2/10 \text{ (see Fig. 1}c\text{)}$$

The voltage generated by this linkage at frequency f

$$= (2\pi f \times 2\pi a/10^9)h^2 = g h^2$$

Now the average value of this voltage between the bottom and the top of the conductor is

$$\frac{1}{H}\int_0^H g h^2\,d\,h = \tfrac{1}{3} g H^2$$

Therefore the actual voltage which produces eddy current at any point h is $g\,(h^2 - \frac{1}{3}H^2)$, because the integral of the eddy current over the whole of the height of the conductor must be zero.

The actual eddy current of the first order at any position h is therefore (see Fig. 1*d*)

$$\frac{g}{\rho}(h^2 - \tfrac{1}{3}H^2)$$

The distribution of this first order of eddy current across the depth of the conductor is therefore parabolic.

With reference to the calculation of the extra losses, we define "extra loss factor" as the ratio of the extra loss due to eddy currents only to the loss which would arise from uniform distribution of current. If all eddy currents beyond the first order can be neglected, the calculation of the extra loss factor is simple. Inasmuch as the first eddy current is at right angles to the initial current, the extra loss in the conductor is proportional to the sum of the square of each element of eddy current, taken over the full depth of the conductor; and the extra loss factor is the ratio of this sum to the sum of the squares of each element of the original uniformly distributed current.

The extra loss factor is therefore

$$\frac{g^2}{\rho^2 H}\int_0^H (h^2 - \tfrac{1}{3}H^2)^2\,d\,h = \frac{4}{45}\cdot\frac{g^2 H^4}{\rho^2} = \frac{4\,d^4}{45} \quad . \quad . \quad (1)$$

where $d = 2\pi H\sqrt{[f a/(10^9\rho)]}$.

It will be found that this result corresponds to the first term of Field's expression when it is expanded in terms of d. With regard to the development of further terms along similar lines, it will be obvious from the operations which are necessary to obtain each fresh term, that they will consist of ascending powers of d^4, i.e. d^8, d^{12}, d^{16}, etc. It would be simple, though laborious, to proceed to discover the coefficient of the next terms of the series, but in most practical cases this is unnecessary.

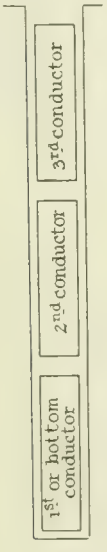


FIG. 1*a*.—Current distribution diagram.

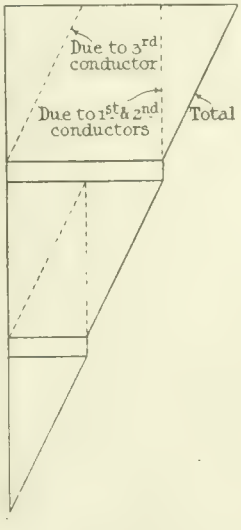


FIG. 1*b*.—Magneto-motive force diagram.

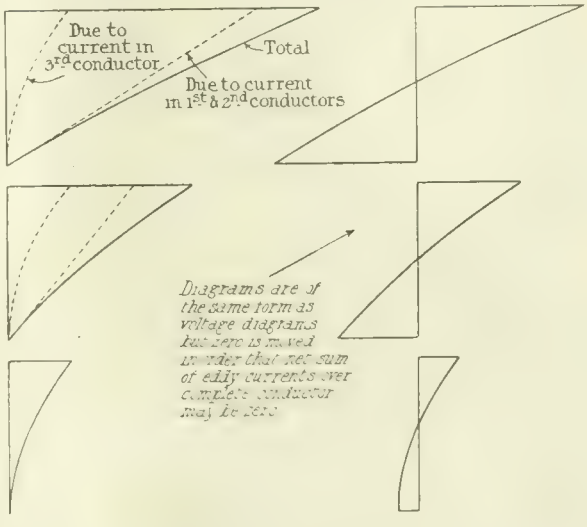

Due to current in 3rd conductor
Total
Due to current in 1st & 2nd conductors
Diagrams are of the same form as voltage diagrams but zero is moved in order that net sum of eddy currents over complete conductor may be zero

FIG. 1*c*.—Flux linkage or voltage diagram.

FIG. 1*d*.—Eddy-current diagram of first order.

The justification for the use of the first term only in most practical cases will be discussed in the next section.

(2) CALCULATION OF A CONDUCTOR HIGHER IN THE SLOT THAN THE BOTTOM.

Deduction of approximate expression.—When we come to consider the eddy-current losses in the second conductor, we find, on referring to Fig. 1, that the flux which passes across the conductor depends not only upon the current in the conductor itself but also upon the currents in the conductor below it.

Starting with our previous assumption of uniformly distributed alternating current of 1 ampere per sq. cm. (see Fig. 1*a*), the total volume of current between the bottom of the slot and any point h in the pth conductor, counting h from the bottom of the pth conductor, is $[h + (p-1)\,H]\,w$.

The magnetizing force at h is $(4\pi w/10)\{h + (p-1)H\}$.

Flux density $= (4\pi w/10)\{h + (p-1)H\}$.

Total flux linkage between h and bottom of conductor $= (4\pi a/10)[\frac{1}{2}h^2 + (p-1)h\,\mathrm{H}]$.

The voltage generated by this linkage at frequency $f = (2\pi f \times 2\pi a/10^8)[h^2 + 2(p-1)h\,\mathrm{H}]$.

The graphical representation of this expression is a parabola of the same form as was found for the bottom conductor, with the addition of a straight line, the slope of which is proportional to the number of conductors below the one in question.

Further, the height of the parabola at the end of the conductor is half the height of the straight line when drawn for one external conductor (see Fig. 1c).

A full appreciation of these points is important in many of the subsequent sections of this paper.

The average value of the last expression between the top and bottom of the conductor is $g[\frac{1}{3}\mathrm{H}^2 + (p-1)\mathrm{H}]$. Therefore the eddy current of the first order at any point h is

$$(g/\rho)\,[(h^2 - \tfrac{1}{3}\mathrm{H}^2) + (p+1)(2h\,\mathrm{H} - \mathrm{H}^2)]$$

The extra loss factor in this case is then

$$\frac{g^2}{\rho^2\,\mathrm{H}}\int_0^{\mathrm{H}}[(h^2 - \tfrac{1}{3}\mathrm{H}^2) + (p-1)(2h\,\mathrm{H} - \mathrm{H}^2)]^2\,dh$$

The result of the integration gives the extra loss factor in the pth conductor (as far as the first order of eddy currents is concerned) as

$$\frac{4}{45}d^4 + \binom{p^2-p}{3}d^4 \qquad \ldots\ldots (2)$$

Where we require the average factor for all the p conductors, the following expression may be derived from the previous one.

The average extra loss factor for p conductors is

$$\frac{4}{45}d^4 + \binom{p^2-1}{9}d^4 \qquad \ldots\ldots (3)$$

Limitation to use of approximate expressions for loss factor.—As already mentioned, the complete expression for the extra loss factor may be given in the form of an infinite series in ascending powers of d^4. The expression consists of two parts, as already shown, the second part involving the number of the conductor under consideration. The first three terms of each part of the expression for the extra loss factor are :

$$(0{\cdot}089\,d^4 - 0{\cdot}00339\,d^8 + 0{\cdot}000138\,d^{12}) + \tfrac{1}{3}(p^2-p)(d^4 - 0{\cdot}041\,d^8 + 0{\cdot}00168\,d^{12})$$

For the lower values of d, the terms of the expressions are convergent from the first term onwards, and when $d = 1{\cdot}1$ the sum of the second and third terms is less than 6 per cent of the first. It is suggested, therefore, that the approximate method may be used without fear of practical error for all values of d up to 1·1.

The height of a solid conductor corresponding to $d = 1{\cdot}1$ when frequency $= 50$, $a = 0{\cdot}75$ and the conductor is solid copper, at approximately 100° C. is 0·54 inch (1·37 cm.).

The losses arising in such a conductor placed at different positions in the slot are given in the following table :—

No. of conductors in slot	Extra loss factor in separate conductors	Average extra loss factor in all conductors
1	0·13	0·13
2	1·11	0·61
3	3·06	1·43
4	5·9	2·55

It will be seen that the limitation fully covers the practical range of conductors.

(3) Depths of Conductor for Minimum Loss and Minimum Temperature Rise.

Depths of conductor for a minimum loss.—It is generally recognized that under given conditions there is a certain depth of conductor, known by writers as the "critical depth of conductor," which gives a minimum loss. This arises out of the fact that when this critical depth is exceeded the rate of increase of the eddy-loss factor is greater than the rate of increase of the depth of the conductor.

This point may be very conveniently investigated by means of the approximate formula just proposed. The total loss factor for any condition may be written $1 + a\,d^4$, where a involves all the coefficients of d^4 in any of the approximate formulæ 1, 2, or 3.

As d is proportional to the depth (H) of the conductor and the normal loss is inversely proportional to H, the total loss in the conductor involving the normal $\mathrm{I}^2\mathrm{R}$ and also the eddy-current loss will be proportional to $1/d + a\,d^3$.

Differentiating this and equating to zero for a minimum value we have $-1/d^2 + 3\,a\,d^2 = 0$, whence $d^4 = 1/(3\,a)$ for the minimum loss.

Putting this value at d^4 in the expression for the extra loss factor we obtain a value of 0·33 for any value of a, so we may say that the value of d or of H (height of the conductor) giving a minimum loss is that value which gives a value of total loss factor equal to 1·33.

It will be noticed that the argument applies not only to individual conductors 1, 2, 3, etc., but also to the average value of the loss factor for all the conductors, for in this case the average loss factor is of the same form but with a different coefficient for d^4, and it has been shown that the conclusion is independent of the value of this coefficient.

It will be noticed that this value, as far as the first conductor is concerned, is slightly outside the range over which it is suggested the approximate formula should be used ; but for the other conductors, and also for the average value of all the conductors, the conclusion is quite legitimate for practical purposes.

Depth of conductor for minimum intensity of heat dissipation.—In many practical cases the actual loss is not so important as the temperature rise which results, and this depends not only upon the total loss, but also upon the facility in dissipating it. It is useful therefore to inquire into the condition which gives a minimum of heat dissipation. This condition will arise when the value of the loss factor increases faster than the square of the depth of the conductor, assuming that most of the heat is dissipated from the sides of the conductor.

If, as before, the extra loss factor equals $a d^4$, then the intensity of heat dissipation is proportional to $(1/d^2) + a d^2$.

Differentiating an equating to zero for minimum value we have $-2/d^3 + 2 a d = 0$, or $d^4 = 1/a$.

Inserting this value of d^4 in the expression for the extra loss factor, we have a minimum intensity of heat dissipation when the factor is unity; that is, the height of the conductor giving a total loss factor of 2 will be that which gives a minimum temperature rise in that conductor.

The same reservation applies as in the previous paragraph to the use of this expression with regard to the first conductor.

(4) Losses in Top Conductors when Subjected to the External Influence of Currents out of Phase with those they themselves carry.

In a full-pitch winding of the two-layer type, the current in the bottom layer is of the same phase as the current in the top layer. If the pitch is fractional, i.e. if the complete coil does not span a complete pole pitch, certain slots will have a current in the bottom layer which is of a different phase from the current in the top layer (see Fig. 2).

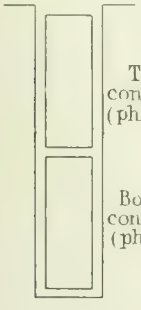


Fig. 2.

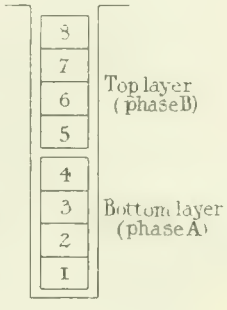


Fig. 3.

The most frequent case occurring in practice is that of a three-phase machine, and in the usual form of winding in which there are six ranges of phase coils in every two poles, the phase differences between the currents in the top and bottom layers in those slots which are carrying two different phases is 60°.

The case just cited, in which each layer consists of one conductor only, is, however, a particular case of the more general case of such a multi-turn coil as indicated in Fig. 3, in which we have 8 isolated conductors.

The losses in the bottom 4 conductors are calculated in the manner already indicated, as they are all carrying current corresponding to, say, phase A.

The fifth conductor, however, is carrying current of another phase, say phase B, but is subjected to the external influence of flux arising from 4 conductors of phase A. Similarly the sixth conductor is carrying current of phase B but is subjected to the external influence of one conductor of phase B and 4 conductors of phase A, and so on.

Considering the case represented in Fig. 2 first, let, in Fig. 4, O A and O B differing in phase by angle ϕ represent the currents in the bottom and top layers respectively. Then resolving phase A into right-angle components, as O C and O D, we have the top conductor subjected—

(*a*) To the influence of its own current and also to the external influence of a current O D in phase with its own current, and

(*b*) To the external influence of current O C at right angles to its own current.

The combined effect under heading (*a*) will be to set up an eddy current of the first order which is at right angles to the currents O B; and the effect of (*b*) will be to set up an eddy current of the first order which is at right angles to the current component O C, that is, in phase with the current O B.

Now the loss factor due to (*a*) may be calculated direct from formula (2) by taking a value of p equal to $1 + \cos\phi$.

The extra loss factor is therefore

$$\frac{4 d^4}{45} + \left(\frac{\cos\phi + \cos^2\phi}{3}\right) d^4 \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

With regard now to condition (*b*) above, the first order of eddy current due to this influence will be

$$K \sin\phi \, (2 h H - H^2)^*$$

Combining this current with the original constant current with which it is in phase, squaring and averaging

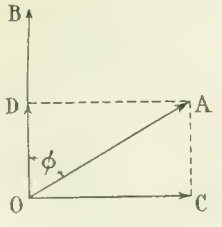


Fig. 4.

Fig. 5.

over the depth of the conductor we find that the extra loss factor due to the condition (*b*) is

$$\tfrac{1}{3} d^4 \sin^2\phi \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

The extra loss factor in the present case from all causes is therefore the sum of (4) and (5), which gives

$$\frac{4 d^4}{45} + \left(\frac{2 \cos^2 \tfrac{1}{2}\phi}{3}\right) d^4 \quad . \quad . \quad . \quad . \quad . \quad (6)$$

In the more general cases where there are m sections in the layers and when we have the tth section in the top layer under consideration, reconsidering the case on the same lines as before, the extra loss factor in this section is given by

$$\frac{4 d^4}{45} + \left[\frac{(m+t)(m+t-1) - 2m(2t-1)\sin^2 \tfrac{1}{2}\phi}{3}\right] d^4 \quad (7)$$

The following expression for the average extra loss factor in all the sections of the top layer may be developed from the last one

$$\frac{4 d^4}{45} + \left(\frac{7m^2 - 1 - 6m^2 \sin^2 \tfrac{1}{2}\phi}{9}\right) d^4 \quad . \quad . \quad . \quad (8)$$

The following expression for the average total loss

* Cf. expression for pth conductor at bottom of page 281.

factor in all sections of both top and bottom layers may also be readily deduced :—

$$\frac{4}{45}d^4 + \left(\frac{(4m^2-1)}{9} - \frac{3m^2(\sin^2\frac{1}{2}\phi)}{9}\right)d^4. \quad . \quad . \quad (9)$$

In each of the last three expressions the first part of the last term relates to the conditions when no phase difference exists between the layers, while the second part gives the reduction when a phase angle ϕ does exist between them.

The correction factors in the above expressions have been developed with reference to the first order of eddy currents. It is easy to show, however, that the same factors apply to the complete expressions developed by Field by substituting new boundary conditions in the determinant

laminate the conductor into a large number of small sections, it may still be possible to divide it into two sections only, and in order that full advantage may be taken of this simple sub-division, it is well to know what relative sections to use in order that the loss in the conductor may be a minimum.

An interesting case of unequal sub-division is indicated in Fig. 5, in which adjacent conductors in a bundle of 6 conductors are unequally divided in order that the separate sections keep their proper places during the insulation process.

We will first consider the case of a bottom conductor divided into two unequal sections, and will then apply the principles established in this case to the calculation of a number of others.

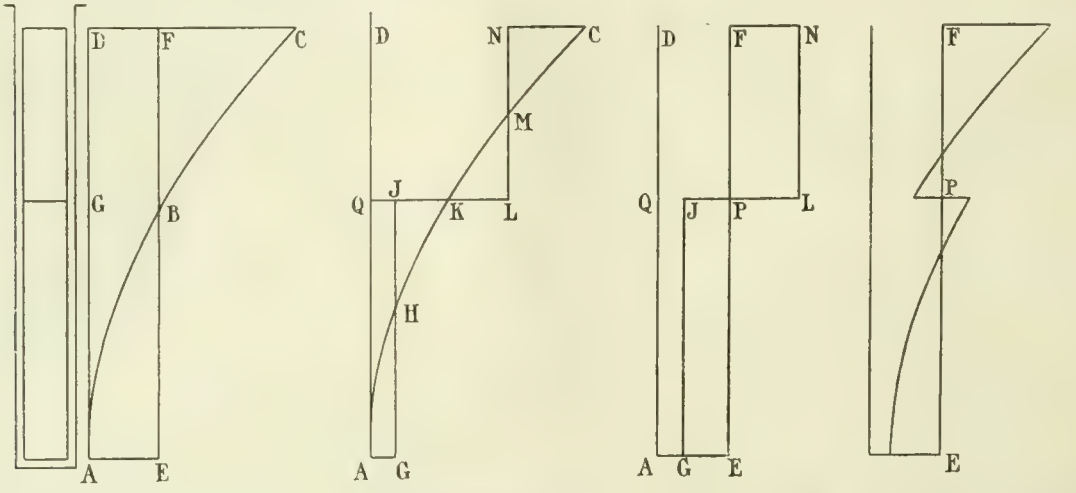


Fig. 6*a*.—Eddy-current distribution in solid conductor.

Fig. 6*b*.—Local eddy current distribution in solid portions of divided conductor.

Fig. 6*c*.—Circulating eddy current between portions of conductor when $b = 1$.

Fig. 6*d*.—Resultant eddy current in divided conductor when $b = 0{\cdot}5$.

Fig. 6.—Diagrams relating to bottom conductor unequally divided.

on page 782 of his paper before the American Institute of Electrical Engineers.

(5) Losses in Conductor Consisting of a Number of Laminations Connected Solidly Together at the Ends.

General considerations.—The losses arising in a conductor divided into a number of sections all connected together at the ends of the conductor are of considerable importance, as this is the simplest method of minimizing the eddy losses.

The case of the infinitely laminated conductor is familiar, and within the range of the present approximate treatment the extra loss factor is that of a solid conductor, reduced by the square of the ratio of the core length to the total length of the conductor, that is, in the ratio $1 : b^2$.

The more practical case of a finite number of laminations will give rise to an extra loss factor intermediate between the solid conductor and the infinitely laminated one.

The question of the equal sub-division of conductors is not the only one of importance, for in some cases where for mechanical reasons it is not considered advisable to

It has already been shown that the eddy currents of the first degree will flow as a result of a voltage represented by a parabolic curve as A B C (Fig. 6*a*). If the conductor were quite solid the eddy-current diagram would be given by the figure A E B F C B A, the height A B being one-third the total height D C of the parabola in order that the "figure of eight" area enclosed may be zero.

If the depth of the conductor A D be divided unequally at Q into portions A Q and Q D, then :—

Firstly, the bottom portion A Q is acted upon internally by the voltage represented by the parabola A H K (Fig. 6*b*), and the top portion Q D is acted on internally by the voltage represented by the continuation of the parabola K M C. If A G represents the average height of the first voltage diagram and Q L represents the average height of the second voltage diagram, then the bottom sections of the conductor will carry a self-contained local eddy current represented by the area A G H J H K A, and the top section of the conductor will carry a self-contained or local eddy current represented by the area K L M N C M K. The losses in each of the unequal sections may be readily calculated from the formulæ (1) and (2) previously given, remember-

ing, however, that the value of p is determined by the intensity of the total magnetization at the top of the section in question in relation to that of its own current.

Secondly, we have the voltage difference represented by the height J L, which is free to send a constant circulating current around the top sections of the conductors. Such a current is uniformly distributed in each section of the conductor. The actual distribution of the voltage or the value of the current density in each of the two sections is obtained as in Fig. 6*c*, considering Q J and Q L with reference to A E the average height of the original diagram.

The current in each section may be considered therefore as consisting of a constant portion and a variable portion. Inasmuch as the average value of the variable portion is zero, it follows that the total eddy loss is the sum of the losses calculated for the constant and variable eddy currents when flowing separately.

Now if the sub-division of the conductor is only carried to the end of the core, both currents are passing through the same resistance and the final distribution of current in the complete conductor will be as in Fig. 6*a*.

The loss due to the circulating current in Fig. 6*c* is therefore the difference between the losses in the whole conductor if solid and the sum of the losses in the separate solid sections.

If, however, the division between sections is continued beyond the core length, the circulating eddy current will have a longer path than the local eddy currents. In fact the ordinates of Fig. 6*c* must be reduced in the ratio of core length to conductor length, and the loss factor due to circulating currents as just found must be reduced in proportion to the square of this ratio. Fig. 6*d* has been drawn to show the total distribution of eddy currents of the first order in the conductor when the divided conductor is twice the length of the core portion.

Putting the argument into general terms, let

K_s = extra loss factor of the complete conductor if solid ;

K_1, K_2, K_3, etc., extra loss factors in the separate laminations due only to local currents, i.e. as if they were separate conductors with reference to conductors of the equal thickness in each case ;

r_1, r_2, r_3, etc., the ratios of the height of the first, second, third, etc., lamination to the total height of the conductor ;

K_c = extra loss factor due to currents circulating between sections ;

and K = extra loss factor in conductor as constructed.

Then the extra loss factor due to local currents in all the laminations is, with reference to the normal loss in the complete conductor,

$$r_1 K_1 + r_2 K_2 + r_3 K_3 + \text{etc.} \quad . \quad . \quad (10)$$

The extra loss due to circulating eddy currents among the laminations is

$$b^2 (K_c - r_1 K_1 - r_2 K_2 - r_3 K_3 - \text{etc.}) \quad . \quad (11)$$

and therefore the extra loss factor due to the combined local and circulating eddy currents is

$$b^2 K_s + (1 - b^2)(r_1 K_1 + r_2 K_2 + r_3 K_3 + \text{etc.}) \quad (12)$$

Conductor unequally divided into two sections.—Applying the general formula to the pth conductor and taking r as the ratio of the upper of the two sections, we find that the extra loss factor is given by the expression

$$d^4 \left[\frac{4}{45} + \frac{p^2 - p}{3} - \frac{(1 - b^2)(3p - r - 1)^2 r(1 - r)}{9} \right] \quad (13)$$

The expression has been put in such a form that the last term shows the reduction in loss factor effected by dividing the conductor. It will be seen that the value of r for a minimum loss may be obtained by differentiating the expression $(3p - r - 1)^2 r(1 - r)$ and equating the result to zero.

The result is the following equation in r :—

$$4r^2 - r(6p + 1) + (3p - 1) = 0$$

By putting successive values of p in this equation and solving it for r we compile the following table :—

No. of conductor	Divisions from top to give minimum loss
1	0·36
2	0·446
3	0·463
4	0·475
Very large	0·5

Consideration of a conductor equally divided into a number of sections.—In this case considerable simplification arises from the fact that all the sections forming the conductor are equal in height. Applying the fundamental formula (2) first to the complete conductor as if solid, and secondly to all the laminations as if they were separate conductors, we find, where n is the number of sections, that the extra loss factor in the pth conductor is given by

$$\left(\frac{d}{n}\right)^4 \left[\frac{n^2}{9} \left\{ 3(p^2 - p) + 1 \right\} - \frac{1}{45} + b^2 c^2 (n^2 - 1) \left\{ \frac{4n^2 - 1}{45} + \frac{n^2 (p^2 - p)}{3} \right\} \right] \quad (14)$$

The factor c is introduced in the above expression to allow for the insulation required between the laminations, as the flux which passes between the laminations across this insulation will increase the circulating current around them. It is the ratio of the total depth of the conductor to the actual depth of copper.

If the average extra loss factor of all the p laminated conductors is required in place of that of the pth conductor above, $\frac{1}{3}(p^2 - 1)$ is substituted for $(p^2 - p)$ in formula (14). When the conductor in question is the tth conductor in the top layer of m conductors and the two layers in the same slot are carrying currents differing in phase by an angle ϕ, then the terms $(p^2 - p)$ in formula (16) are replaced by

$$(m + t)(m + t - 1) - 2m(2t - 1)\sin^2 \tfrac{1}{2}\phi \quad (14a)$$

The application of the modifications of this expression in formulæ (8) and (9) to the present case of laminated conductors will be apparent.

Fig. 7 has been plotted from the formulæ in this section and relates :—

(*a*) (Full lines) to a conductor of a total depth of copper 0·5 inch (frequency = 50, $a = 0{\cdot}7$, $b = 0{\cdot}5$ and $c = 1$ for the sake of example) divided into different numbers of laminations, namely into 2, 3, 4, and 5 parts to give the same total depth. Different curves relate to the first, second, third, and fourth of such conductors from the bottom of the slot.

(*b*) (Dotted lines) to similarly laminated third and fourth conductors in slots where current in top conductors differs in phase from current in bottom conductors by 60°.

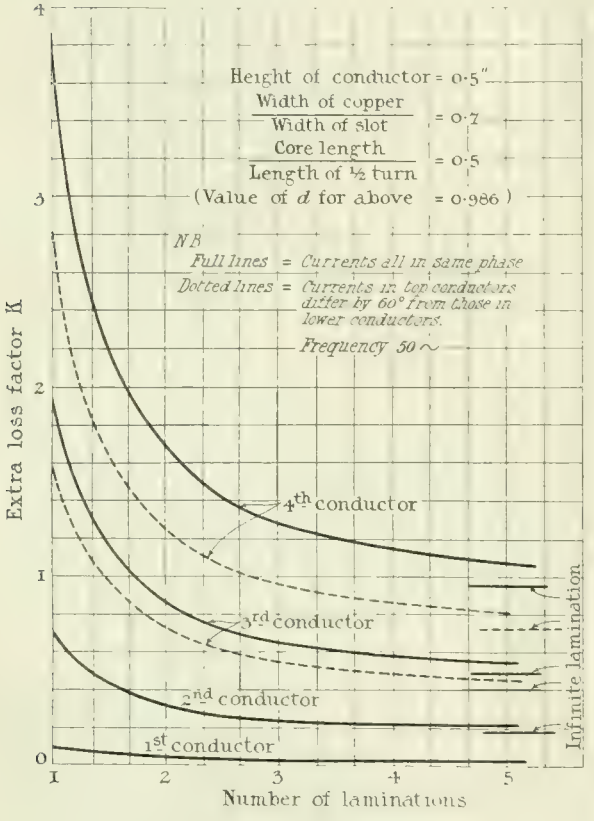


FIG. 7.—Extra loss factor in laminated conductors.

Loss in equally laminated conductors subjected to external influence only.—The case of a conductor not carrying current of its own yet subjected to the external influence of other conductors is of interest in some later problems.

The loss in a solid conductor due to an external influence corresponding to $(p-1)$ is represented by

$$\tfrac{1}{3} d^4 (p-1)^2 . \quad . \quad . \quad . \quad . \quad . \quad (15)$$

Using this expression, we find that in an equally laminated conductor the loss factor, i.e. the loss compared with the normal loss in a conductor of the same size carrying the fundamental current, is

$$(d/n)^4 . \tfrac{1}{3} (p-1)^2 . n^2 \left\{ 1 + b^2 c^2 (n^2 - 1) \right\} \quad . \quad . \quad (16)$$

(6) LOSSES IN COILS IN WHICH INSULATED LAMINATIONS ARE CONTINUED FROM TURN TO TURN.

General considerations.—The improvement effected by simple laminations as discussed in the last section is often not sufficient for practical purposes, and it is now proposed to discuss various arrangements by which further improvement is effected by continuing the separately insulated laminations of the conductor from turn to turn, and sometimes from coil to coil, throughout the winding. Field, in his paper, discussed a number of these cases with reference to his equations. They may, however, be conveniently studied with reference to only the first order of eddy-current distribution already deduced. It is proposed to review briefly the well-known cases and then to consider certain new ones, including those in which the coil has a fractional pitch.

Now the parasitic voltage corresponding to the eddy currents of the first order can be represented by parabolas and straight lines as already shown in Fig. 1. It will be noted that the slope of the straight line, starting from the second, increases from conductor to conductor and may be represented in any conductor, say the pth, by the figure $(p-1)$; that is, for the fourth conductor the slope of the straight line may be represented by 3, and so on.

It will also be noticed that the final height of the parabola for each conductor is the same, and is half the final height of the straight line which represents the unit slope in the second conductor.

If now the laminations of any one conductor are connected continuously to the corresponding laminations of any other conductor, the resulting parasitic voltage in the two conductors will be represented by the sum of the parabolas and straight lines relating to these two conductors. Most of the cases to be considered will not have the voltages added in this manner, for in passing through one slot to the next the laminations are reversed, so that the top of the voltage diagram of the one conductor will need to be added to the bottom of the voltage diagram of the other conductor. Some actual diagrams are given later in illustrating particular cases.

The problem may be considered by simple algebra as follows :—

The parasitic voltage of the pth conductor is indicated (leaving out constant terms and constant coefficients) by the expression $\frac{1}{2} h^2 + (p-1) h$. When, however, we wish to consider the parasitic voltage in a conductor with reference to the reversed order of the laminations, we must change the variable h to $(H - h)$, so that the expression for the parasitic voltage of the pth conductor under these conditions is $\frac{1}{2}(H-h)^2 + (p-1)(H-h)$, or $\frac{1}{2} h^2 - p h$, leaving out constant terms and coefficients as before.

In considering, therefore, the resulting voltage per unit length, say in the second and fifth conductors, when the laminations of one of these is reversed, the expression will be $\frac{1}{2} [\frac{1}{2} h^2 + 4 h + \frac{1}{2} h^2 - 2 h]$, i.e. $\frac{1}{2} h^2 + h$, whence the equivalent value of p is 2.

CONSIDERATION OF SPECIAL CASES OF CONTINUOUSLY INSULATED LAMINATIONS.

We will now proceed to consider in detail some of the cases which arise in practice, designating them by the names usually given to the types of winding to which they

refer, and remembering that in all cases, unless otherwise stated, the order of laminations is reversed on opposite sides of the coil.

Case I. Single-layer single turn.—The diagrammatic treatment of this case is shown in Fig. 8. The first half turn of the coil is shown in Fig. 8*a* and the second half turn of the coil is shown in Fig. 8*b*. The electromotive force diagrams are both shown on the curves of Fig. 8*c*, but one is reversed because of the reversing of the laminations.

be the same as the loss in a conductor of half the original depth. When the conductor is infinitely laminated, the extra loss factor in the coil is one-sixteenth the value for a single infinitely laminated conductor.

Case II. Windings in which the order of the laminations is reversed at intervals.—The case just considered is typical of several others. For instance, if any other conductor than the first, say the third, be caused to occupy a similar position in another slot after being reversed, then the straight-line portion of the voltage diagrams will

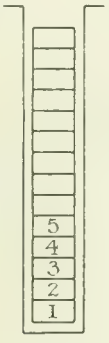


FIG. 8*a*

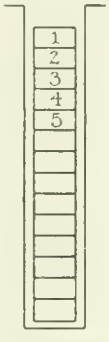


FIG. 8*b*

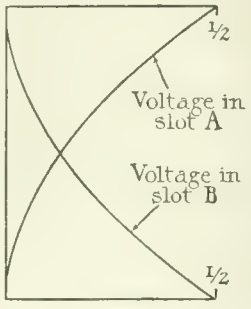


FIG. 8*c*

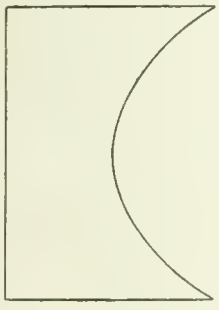


FIG. 8*d*.—Combined voltage of slots A and B.

FIG. 8*e*. — As Fig. 8*d* with zero moved and ordinates reduced by one-half.

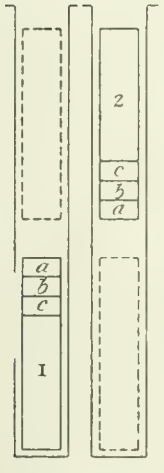


FIG. 9*a*.—Arrangement of conductors in slots.

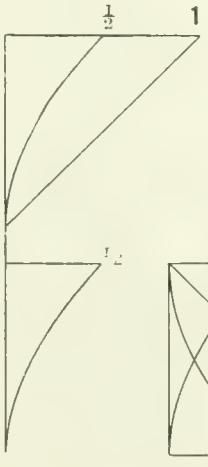


FIG. 9*b*.—Voltage diagrams of conductors.

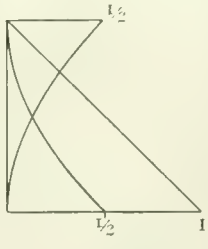


FIG. 9*c*.—Voltages of conductors superposed.

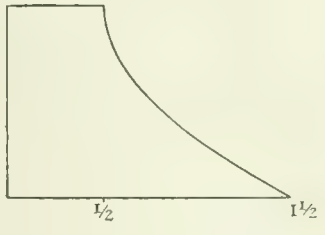


FIG. 9*d*.—Voltage diagrams combined.

In Fig. 8*c* it will be seen that the result is a parabola reflective about the centre of the conductor but of the same magnitude as before. This leads to the rule based upon Field, viz. for a one-layer winding in which the conductor is twisted over the middle of the coil the eddy current is as for a first conductor of half the depth.

The algebraical analysis of this case is as follows:—

The resulting voltage is $\frac{1}{2}(\frac{1}{2}h^2+\frac{1}{2}h^2-h)=\frac{1}{2}h^2-\frac{1}{2}h$, which corresponds to a conductor of the degree $\frac{1}{2}$.

The loss in such a conductor may readily be shown to balance one another and the extra loss factor due to circulating currents in this third conductor will be as for a first conductor of half the depth.

The same principle may be applied to complete coils or even to whole ranges of coils.

Case III. Double-layer single-turn coil.—Fig. 9 has been drawn for this case. The result is that after dividing the ordinates of Fig. 9*d* by 2, the loss factor due to circulating current in each conductor is as for the first conductor.

Case IV. Double-layer multiple-turn coil, lamination being

continuous throughout coil and reversed at each end.—Again the general rule may be briefly stated. The loss factor due to circulating currents is as for conductor of a degree corresponding to one-quarter the number of conductors per slot, plus ½ (see Figs. 10*a* and 10*c* for a two-turn coil).

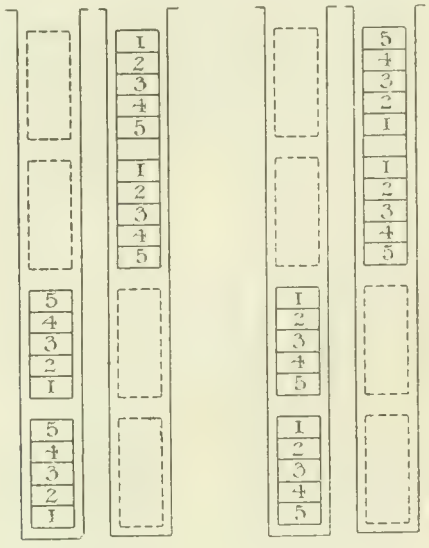


FIG. 10*a*.

FIG. 10*b*.

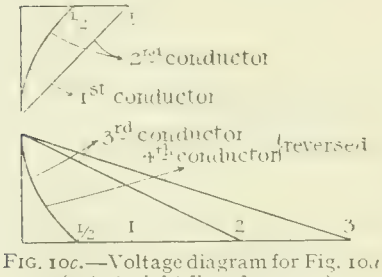


FIG. 10*c*.—Voltage diagram for Fig. 10*a* (net straight-line slope = 4).

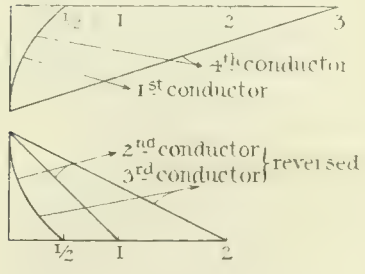


FIG. 10*d*.—Voltage diagrams for Fig. 10*b* (net straight-line slope =0).

Case V. Double-layer multiple-turn coil, laminations being continuous throughout coil, modified construction for coils with even number of turns.—The partial elimination of the straight lines by one another in the previous case gives rise to the question whether it is possible to arrange the laminations in the successive half turn of the multiple half coil so that the straight lines eliminate one another altogether. If this can be done, the loss due to circulating current in each conductor of the coil is obviously reduced to that of a first conductor of half the depth of the conductor in question, as in Case I.

We may attain the desired object if we reverse the conductors, not with reference to their layer, but with reference to the slope of the straight-line portion of their parasitic voltage diagrams. For instance, in the case of a two-turn coil this may be done by connecting the first and fourth conductors so that they are cumulative and are opposed to the second and third conductors, which in themselves are cumulative as shown in Fig. 10*b*. The resulting voltage diagrams are shown in Fig. 10*d*.

In the case of an infinitely laminated conductor the extra loss factor will be reduced from

$$b^2 d^4 \left(\frac{4}{45} + \frac{1}{4}\right) = 31 \frac{b^2 d^4}{180}$$

for a conductor of degree 1½, to $b^2 d^4/180$ for a conductor of degree ½.

A comparison of the algebraical treatment of Cases IV and V for a two-turn coil is of interest.

In the arrangement of Case IV the resulting expression will be :—

$$\tfrac{1}{4}[(\tfrac{1}{2}h^2 - h) + (\tfrac{1}{2}h^2 - 2h) + (\tfrac{1}{2}h^2 + 2h) + (\tfrac{1}{2}h^2 + 3h)] = \tfrac{1}{2}h^2 + \tfrac{1}{2}h$$

which corresponds to a 1½ conductor (see rule given above).

The arrangement of Case V will give

$$\tfrac{1}{4}[(\tfrac{1}{2}h^2 - h) + (\tfrac{1}{2}h^2 - 4h) + (\tfrac{1}{2}h^2 + h) + (\tfrac{1}{2}h^2 + 2h)] = \tfrac{1}{2}h^2 - \tfrac{1}{2}h$$

which corresponds to a conductor of degree ½, as already deduced by the graphical method.*

Case VI. Double-layer multiple-turn coil, laminations being continuous throughout the coil—modified construction for a coil with an odd number of turns.—The complete elimination of the straight portion of the parasitic voltage diagrams is not possible in this case, as the sum of the slope of all the straight portions of the parasitic voltage diagram is odd, but the same final result—that is, making the circulating current in the coil equivalent to that of the first conductor of half the depth—may be attained by so arranging the order of lamination in the various conductors that a single unbalanced straight element of the voltage diagram remains and is in opposition to two unbalanced parabolic elements.

Thus in a three-turn coil, if instead of the laminations of the first, second, and third conductors being connected together in cumulative effect, and in opposition to the cumulative effect of the fourth, fifth, and sixth conductors, we connect the first, second, third and fifth conductors to be cumulative and to be in opposition to the cumulative effect of the fourth and sixth conductors, the circulating-current losses will be as for a conductor of half the original height.

The algebraic treatment for a three-turn coil may be given as follows :—

1. For the usual arrangement

$$(1/6)\ [(\tfrac{1}{2}h^2 - h) + (\tfrac{1}{2}h^2 - 2h) + (\tfrac{1}{2}h^2 - 3h) + (\tfrac{1}{2}h^2 + 3h) + (\tfrac{1}{2}h^2 + 4h) + (\tfrac{1}{2}h^2 + 5h)] = \tfrac{1}{2}h^2 + h$$

which is equivalent to the second conductor.

* For further particulars of this type of coil see British Patent 135,533.

2. For the modified arrangement

$$(1/6)\left[\tfrac{1}{2}h^2 - h) + (\tfrac{1}{2}h^2 - 2h) + (\tfrac{1}{2}h^2 - 3h) + (\tfrac{1}{2}h^2 - 5h) + (\tfrac{1}{2}h^2 + 3h) + (\tfrac{1}{2}h^2 + 5h)\right] = \tfrac{1}{2}h^2 - \tfrac{1}{2}h$$

the result again corresponding to a conductor of the degree $\frac{1}{2}$.

In the case of an infinitely laminated conductor the extra loss factor is reduced from $d^4\left(\frac{4}{45} + \frac{2}{3}\right) = 0{\cdot}76\ b^2 d^4$ for a conductor of degree 2, to $\frac{b^2 d^4}{180} = 0{\cdot}0056\ b^2 d^4$ for a conductor of degree $\frac{1}{2}$.*

Reconsideration of Laminated Coils when Used in Fractional Pitch Windings.

We will reconsider some of the previous cases when the coils span a fractional portion of a pole pitch, re-designating them by the suffix *a* in order to facilitate reference. In addition, under suffix *b* we will combine the previous cases with the present ones, as with a fractional pitch which is less than the distribution of a phase.

Case IIa.—In the types of winding falling under this heading, the conductors are sorted into pairs, so that each conductor of a pair is similarly situated both as regards position in the slot and as regards external influence, but the order of the laminations is reversed in the second conductor of the pair. As in the previous Case II, the loss in the conductors due to circulating current will be as for a first conductor of half the depth.

Case IIIa. Two-layer single-turn coil.—This case is typical of others which follow. The expression for the parasitic voltage for the side of the coil which is at the bottom of a slot is (when laminations are reversed) $\frac{1}{2}h^2 - h$.

The expression for the parasitic voltage on the side of the coil, which is at the top of a slot, is $\frac{1}{2}h^2 + h\cos\phi + jh\sin\phi$.

The parasitic voltage in each conductor of the complete coil is therefore

$$\tfrac{1}{2}\left[\tfrac{1}{2}h^2 - h + \tfrac{1}{2}h^2 + h\cos\phi + jh\sin\phi\right] = \tfrac{1}{2}h^2 + \tfrac{1}{2}h\left[\cos\phi - 1\right] + \tfrac{1}{2}jh\sin\phi$$

Referring to section (4), and especially formulæ (4) and (5), it will be seen that the extra loss factor in a conductor with this parasitic voltage distribution will be

$$b^2 d^4\left[\tfrac{4}{45} + \tfrac{1}{3}d^4\left\{\left(\tfrac{1}{2}\cos\phi + \tfrac{1}{2}\right)\left(\tfrac{1}{2}\cos\phi - \tfrac{1}{2}\right) + \tfrac{1}{4}\sin^2\phi\right\}\right]$$

The second part of the expression becomes zero upon simplification, and thus the phase angle ϕ does not enter into the result, and the losses are as for a first conductor as in the allied Case III.

Case IIIb. Two-layer single-turn coil with laminations continued from coil to coil.—The further case where the insulated laminations of coils such as considered in Case III are continued from coil to coil, and where only some of the coils are subjected to the external influence of current of a different power factor, is worthy of consideration.

Let the number of coils thus subjected to the external current influence out of phase with their own current be a fractional part, say *s*, of the total number of coils connected in series; then the average parasitic voltage of all the conductors in the combined coils will be

$$\tfrac{1}{2}h^2 - \tfrac{1}{2}sh + \tfrac{1}{2}sh\cos\phi + \tfrac{1}{2}jsh\sin\phi$$

and the portion of the expression for the extra loss factor which involves the equivalence of the conductor in the form $(p^2 - p)$ is

$$\tfrac{1}{2}s(\cos\phi - 1)\left[\tfrac{1}{2}s(\cos\phi - 1) + 1\right] + \tfrac{1}{4}s^2\sin^2\phi = -s(1-s)\sin^2\tfrac{1}{2}\phi \quad (17)$$

From this it will be seen that a reduction in loss factor may be obtained by continuing the insulation of the laminations from coil to coil. The maximum effect occurs when $s = 0{\cdot}5$, and this corresponds to a fractional pitch of 5/6 for a three-phase machine and a fractional pitch of $\frac{3}{4}$ for a two-phase machine.

Case IVa. Two-layer multiple-turn coil, laminations being continuous throughout the coil.—This case may be treated in the same manner as Case III*a* for a single-turn coil, with a similar result, namely, that the loss factor is independent of the phase of the external influence on the top side of the coil.

Case IVb, Case IV, and IVa combined.—Here again the result is similar to Case III*b*, for the equivalent value of the conductor is reduced. When the coils have *m* turns, the equivalence of the winding in the form $(p^2 - p)$ is

$$\tfrac{1}{4}(m^2 - 1) - m^2 s(1-s)\sin^2\tfrac{1}{2}\phi \quad . \quad . \quad . \quad (18)$$

Case Va, double-layer multiple-turn coil, laminations continuous throughout coil, modified construction for coils with even number of turns.—The essential feature of this construction is that alternate adjacent conductors in each layer are reversed, whereas in Case IV the laminations of adjacent conductors in each layer are of the same sequence but are reversed in the two layers. In the present case therefore the conductors in the top layer are alternatively under the direct and reversed influence of the current in the bottom layer, whatever their phase may be, and as the number of conductors per layer is even, the loss factor is independent of the influence in the bottom layer, whatever its value or phase. The current and therefore also the loss factor are exactly the same as in the previous Case V, and the case corresponding to Cases III*b* and IV*c* does not arise.

Case VIa. Double-layer multiple-turn coil, laminations being continued throughout the coil-modified construction for the coil with an odd number of turns.—An essential feature of this construction is again that alternate adjacent conductors in the top layer are reversed. As the number of conductors in the layer is odd, it follows that the external influence of the out-of-phase current in the bottom of the slot is balanced except as regards one conductor, whatever the number of conductors or turns per coil. It follows, therefore, that the average parasitic voltage per conductor in the coil is given by the expression

$$\tfrac{1}{2}h^2 + h\left(\tfrac{1}{2}\cos\phi - 1\right) + \tfrac{1}{2}jh\sin\phi$$

The value of $(p^2 - p)$ for such a conductor will be found to be

$$\sin^2\tfrac{1}{2}\phi - \tfrac{1}{4} \quad . \quad . \quad . \quad . \quad . \quad . \quad (19)$$

a result which is not independent of ϕ but is independent of *m*.

For a three-phase machine the equivalent conductor is

* For further particulars of this type of coil see British Patent 13°,202.

unity instead of 0·5 in Case VI, and for a two-phase machine is 1·2 In no case, however, is the loss so great as in Case IV, IV*a* and IV*b*, which all involve the value of m.

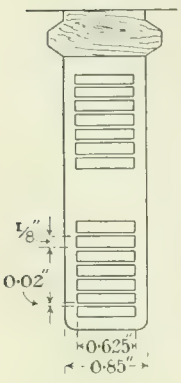
Case VI b.—Reconsidering Case VI*a* in the same way as previous cases, the equivalent conductor when expressed in the form $(p^2 - p)$ will be found to be

$$s^2 \sin^2 \tfrac{1}{2}\phi - \tfrac{1}{4} \quad . \quad . \quad . \quad . \quad . \quad (20)$$

a result which is intermediate between Case VI and Case VI*a*.

Calculation of Losses in Coils with Continuously Insulated Laminations.

Where the laminations are so thin that the case of infinite lamination is approached, the loss factor for the whole coil may be determined by using the equivalent



(A) Extra Loss Factors due to Local Currents.

1st Conductor	0·022
2nd Conductor . ..	0·150

(B) Extra Loss Factors due to Circulating Currents—Each Conductor.

Case III and Case IIIA (3 phase)	Case IIIB (3-phase 5/6 pitch)
0·308	0·232

(C) Extra Loss Factor from All Causes.

	Case III or Case IIIA (3-phase)	Case IIIB (3-phase 5/6 pitch)
1st Conductor	0·33	0·25
2nd Conductor	0·46	0·39
Average .	0·40	0·32

(D) If Each Conductor had had Lamination separately connected at this End, Extra Loss Factors from All Causes would have been (approximately)—

1st Conductor	0·3
2nd Conductor	2·5
Average	1·4

Fig. 11.—Calculation of extra loss factors in a single-turn two-layer coil (temperature of copper taken as 100° C.).

$b = 0{\cdot}53$; frequency = 50.
Cases IIIA and IIIB are for 3 phase 5/6 pitch.

value of $(p^2 - p)$ deduced under the previous headings in formula (2), multiplying the result by $b^2 c^2$.

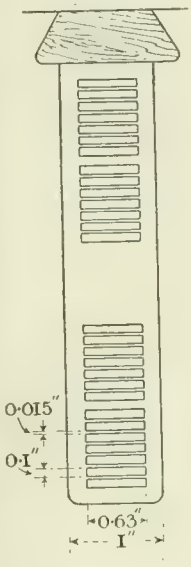
In most practical cases, however, the finite thickness of the lamination must be taken into account, and for this purpose formulæ (13) and (13*a*) should be used. The following points, however, should be noted :—

(1) p, m or l in the first portion of these formulæ, i.e. in the portion dealing with the local currents, is the actual number of the conductors as they appear in the coil, as the loss due to local currents in the laminations is independent of the manner in which the coil has been constructed.

(2) For the circulating-current losses the second portion of formula (13) should always be used in all cases, and the value of $(p^2 - p)$ in this is the same for every conductor and is the equivalent of the coil, as derived under the previous headings in this section.

As illustrations of calculations, Figs. 11, 12 and 13 are given showing details and results for a one-turn, a two-turn, and a three-turn coil respectively.

In concluding this section it may be added that the equivalent values of $(p^2 - p)$ as here deduced for the various cases are applicable to the calculation of deep infinitely-laminated conductors for which Field's full expressions must be used. They may all be derived by



(A) Extra Loss Factor due to Local Currents.

1st Conductor	0·007
2nd Conductor	0·047
3rd Conductor .. .	0·128
4th Conductor	0·249

(B) Extra Loss Factor due to Circulating Currents

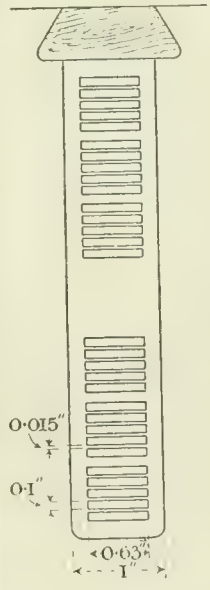
	Case IV or Case IVA	Case V	Case IVB
Equivalent Conductor (P)	1½	½	(1·300
$(P^2 - P)$	0·75	−0·25	0·5
Factor for all Conductors	0·613	0·0096	0·402

(C) Extra Loss Factor for All Causes.

	Separate Conductor	Case IV or Case IVA	Case V	Case IVB
1st Conductor	0·2	0·62	0·017	0·409
2nd Conductor	1·3	0·66	0·057	0·509
3rd Conductor	3·8	0·74	0·138	0·590
4th Conductor	7·4	0·80	0·250	0·711
Average ..	3·2	0·72	0·12	0·57

Fig. 12.—Calculation of extra loss factor in a two-turn two-layer coil (temperature of copper taken as 100° C.).

$b = 0{\cdot}70$; frequency = 50.
Cases IVA and IVB are for 3-phase 5/6 pitch.



	Extra Loss Factor due to Local Currents	Extra Loss Factors if Each Conductor were Separate
1st Conductor ..	0·003	0·04
2nd Conductor ..	0·024	0·36
3rd Conductor ..	0·064	0·90
4th Conductor ..	0·025	1·04
5th Conductor ..	0·207	3·19
6th Conductor ..	0·308	4·77
Average ..	0·122	1·88

Extra Loss Factors due to Circulating Currents.

	Case IV	Case VI	Case VIA	Case VIB
Equivalence of Conductor (P)	2	½	1	⅓
$P^2 - P$	2	¼	0	3/10
Factor for all Conductors	0·341	0·002	0·040	0·011

Total Extra Loss Factors.

	Case IV	Case VI	Case VIA	Case VIB
1st Conductor ..	0·344	0·005	0·043	0·014
2nd Conductor ..	0·365	0·026	0·064	0·035
3rd Conductor ..	0·405	0·066	0·104	0·075
4th Conductor ..	0·466	0·127	0·165	0·136
5th Conductor ..	0·548	0·204	0·247	0·218
6th Conductor ..	0·649	0·310	0·348	0·319
Average ..	0·46	0·12	0·16	0·13

Fig. 13.—Calculation of extra loss factors in a three-turn two-layer coil (temperature of copper taken as 100° C.).

$b = 0{\cdot}7$; frequency = 50.
Cases VIA and VIB are for 3-phase 5/6 pitch.

introducing the proper boundary condition in the previously mentioned determinant in Field's paper.

(7) Losses in Conductors and Coils in which Insulated Laminations are Successively Transferred.

There are two different methods of carrying out successive transference, viz. when the conductor takes the form of a rope or cable and each lamination of the conductor occupies all positions in the one conductor, and when the laminations of a normal conductor are continued throughout the winding and are transferred to adjacent positions at the end of each turn.*

When the cycle of transference is complete, the losses depend only upon the finite thickness of the single laminations and, apart from mechanical and other restrictions in the design, may be continuously reduced by choosing a greater and greater number of laminations to form the conductor, each such lamination forming, as far as eddy currents are concerned, an isolated conductor.

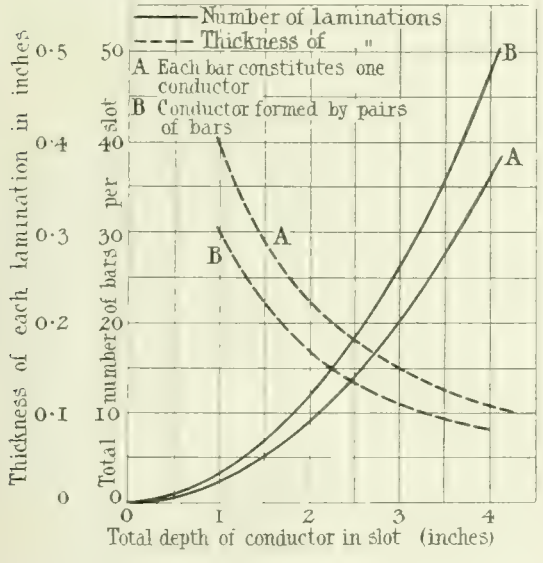


Fig. 14.—Number and thickness of laminations for different total depths of copper to give an extra loss factor of 0·33.

The second method has the limitation that the number of laminations in the conductor is limited to the number of turns per phase in the winding, and in some cases further means must be adopted to reduce the eddy-current losses in the finite sections.†

Curves are plotted in Fig. 14 showing the number of laminations into which a given total depth of copper must be divided in order that the method of successive transference may reduce the extra loss factor to a given value, in particular say to 0·33. In addition the thickness of the laminations has also been indicated.

The curves have been plotted by supposing in formula (3) that $\frac{p^2}{9}$ is so large compared with the constant arithmetical term $(-1/45)$ that the latter can be neglected.

* See British Patent 10919/13.
† See however British Patents 30 062 and 30,063 of 1919.

The number of laminations in the slot (p) is given by

$$p = \frac{H^2 f a}{27 K} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (21)$$

and when $f = 50$, $a = 0{\cdot}7$, and $K = 0{\cdot}33$, $p = 2{\cdot}25\ H^2$.

Similar useful approximate formulæ may be derived from formula (13) when the laminations are transferred in groups. For instance, if each separate conductor consists of two laminations solidly connected at the end of each half turn, then

$$p = \frac{H^2 f a}{54} \sqrt{\left[1 + \frac{3 b^2 c^2}{K}\right]} \quad . \quad . \quad . \quad . \quad (22)$$

and if $f = 50$, $a = 0{\cdot}7$, $b = 0{\cdot}5$, $c = 1$, and $K = 0{\cdot}33$ $p = 1{\cdot}5\ H^2$, and the number of laminations is twice this number. This case is also plotted in Fig. 14.

The calculation of the loss factor in cases where the cycle of transference is complete is comparatively simple. In cases, however, where the cycle of transference may not be complete, circulating currents will occur between the various laminations which cause an addition to the loss factor.

In the cable construction, incomplete transference will occur when the length of the core of the machine does not correspond to an exact number of pitches in the conductor.

A similar consideration will arise in the case of the second method described above, when the number of turns, for some reason arising out of the details of the design, does not correspond to the number of sections selected for the conductor, as for instance when the number of turns per phase is 9 and the number of laminations selected is say 6 or 12. Further cases arise when the winding has a fractional pitch; for although the cycle of transference may be completed mechanically, it will then not be satisfied electrically.

Calculation of Loss Factors when Cycle of Transference is Incomplete.

It will be noticed, first of all, that the complete cycle consists of a double traverse of the conductor. In Fig. 15, however, diagrams have been drawn to show the regions of the conductor traversed by laminations when only three-tenths of a cycle of transference has been completed, the different individual diagrams marked *a*, *b*, *c*, etc., referring to laminations originally situated at different positions in the conductor. The actual initial position of the lamination under consideration is shown by a thick line in each diagram.

In addition to the conductor itself, we have also shown the parasitic voltage distribution when the conductor is a first conductor, and on these parasitic voltage diagrams we have indicated the portions which will be generated in a lamination corresponding to each of the diagrams *a*, *b*, *c*, etc. The parasitic voltage for the laminations on the right-hand side of the conductor have been drawn in continuation of that for the left-hand side of the conductor.

It may be noted in passing that the minimum average voltage will be for the position shown as *i* in diagram and the maximum average voltage will be for the position shown in diagram *d*.

Now in order to calculate the circulating eddy current between the laminations, we proceed first of all to determine the average parasitic voltage in the various lamina-

tions over the completed portion of the cycle. Simple algebra and integrations show that if, leaving out constant terms and coefficients, we take the expression for parasitic voltage distribution as h^2, then the parasitic voltage diagram for the partially transferred conductor is symmetrical about the positions i and d (see Fig. 16) and that for the region of the conductor between the position i and f that is for $(1-r)$th portion of the depth of the conductor, the parasitic voltage expression is (with reference to position d as origin) still h^2; while for the rest, that is rth, of the depth of the conductor between d and f the expression (with reference to d as origin) is $-h^2(1-r)/r + H^2(1-r)$.

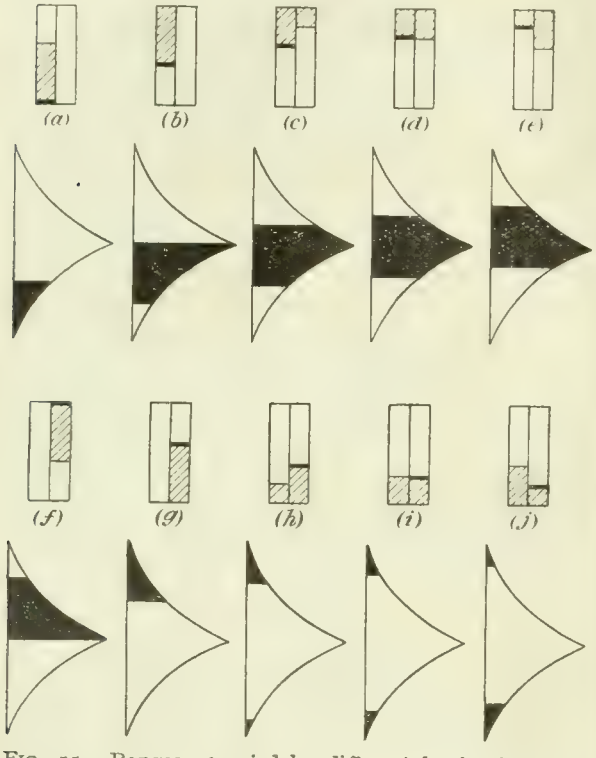


FIG. 15.—Ranges occupied by different laminations and parasitic voltages accumulated in them when 3/10ths of cycle of transference is completed.

When the conductor is infinitely laminated the extra loss in the portion of the conductor between f and i will be

$$(4/45)\, d^4 (1-r)^5 \quad . \quad . \quad . \quad . \quad . \quad (23)$$

and similarly, the extra loss of the portion of the conductor between d and f will be

$$(4/45)\, d^4 (1-r)^2 r^3 \quad . \quad . \quad . \quad (24)$$

again with reference to the whole conductor.

In addition to the extra loss factors above, there is that due to a circulating of eddy current between the two portions of the conductor, for the average value in each is not the same. The difference between the average voltages in the two regions is $\frac{2}{3} H^2 (1-r)$.

The resistance of the path of the circulating current is proportional to $\frac{1}{r(1-r)}$, so that the extra loss will be

$$(4/9)\, d^4 r (1-r)^3 \quad . \quad . \quad . \quad . \quad . \quad (25)$$

This extra loss is independent of the degree of lamination. The extra loss factor in the conductor will therefore be, in the case of infinite lamination,

$$(4/45)\, d^4 (1-r)^2 \left\{(1-r)^3 + r^3 + 5r(1-r)\right\}$$
$$= (4/45)\, d^4 (1-r)^2 (1-2r-2r^2) \quad (26)$$

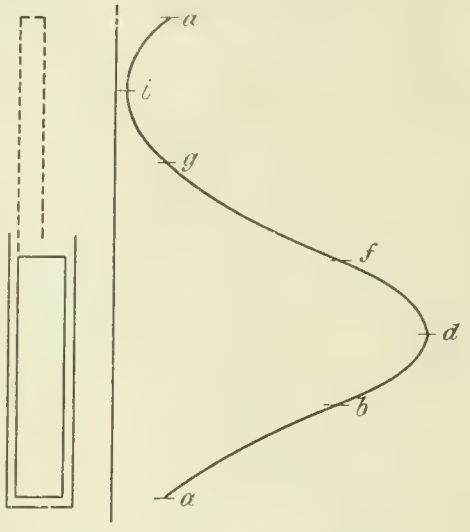


FIG. 16.—Average parasitic voltage in laminations of first conductor when 3/10ths of cycle of transference has been completed.

(Letters a, b, d, etc., refer to corresponding lamination in Fig. 15. a, b, d, etc.)

Taking the loss in an ordinary infinitely laminated conductor as $(4/45)\, d^4$, the decreased ratio of loss obtained by partial transference is given by $(1-r)^2(1-2r-2r^2)$. This expression is plotted in Fig. 17.

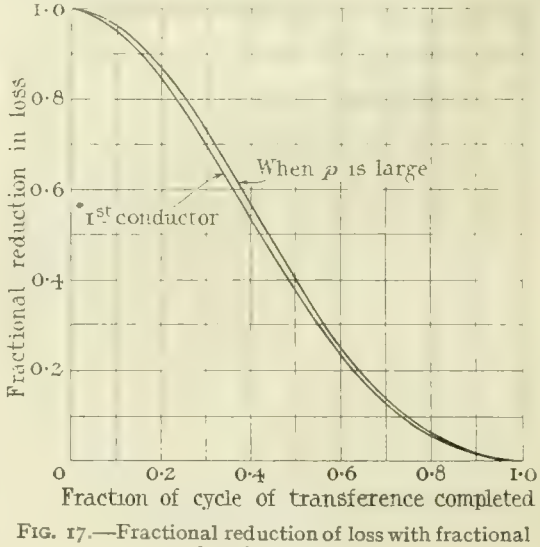


FIG. 17.—Fractional reduction of loss with fractional cycles of transference.

These results apply to the bottom conductor only. The cases of other conductors have been analysed, but the resulting curve is so close that for all practical purposes it

may be taken as identical with it. We may simply state that when p is very large the reduction factor

between $r=0$ and $r=0{\cdot}5$ is $[1-4r^2+(16/5)r^3]$

and between $r=0{\cdot}5$ and $r=1$ is

$$\left(\frac{1-r}{r}\right)^2\left\{1-\frac{8r+28r^2-16r^3}{5}\right\} \quad . \quad (27)$$

Calculation of Loss Factor when Transference is Continued past the First Cycle but Subsequent Cycles of Transference are Incomplete.

At the end of the first cycle of transference there is no parasitic voltage between the various laminæ of the conductor. As subsequent cycles are entered upon, the parasitic voltage will gradually reappear, and will attain for corresponding positions in the cycle the same value as in the first cycle. In the new cases, however, the eddy currents which will result from this voltage have to traverse a longer distance of conductor and will be reduced accordingly. This is equivalent to decreasing the value of b. For instance, if the winding occupies one complete cycle and half of the next, the voltage corresponding to one-half of the cycle is now acting apart from end connections over a length of conductor equal to three halves, instead of one-half of one cycle. The value of b is therefore one-third of its previous value and the extra loss factor due to circulating currents is diminished in the ratio of 1:9.

It will be seen that when once a cycle of transference has been completed, the unbalanced voltages due to the ncompletion of any subsequent cycles when distributed over the whole conductor are small, and the resultant loss rapidly becomes negligible.

Calculation of Loss Factor when Transference of Laminations takes place in Steps at Ends of Turns.

The distinction between this type of construction and that previously considered is that the transference of the lamination in two successive positions takes place in steps, viz. by taking what is for the time being the top lamination and placing it at the bottom of the conductor. Only a single width of lamination is required across the slot for this construction and the cycle of transference is thus completed by a single traverse of the conductor.

A consideration of the present problem shows that, as in the previous one, the conductor is divided into two ranges consisting of $(n-r+1)$ and $(r-1)$ laminations respectively, and that a portion of the loss factor is derived from each range. There is in addition a circulating current between the ranges which give rise to another term in the loss-factor formula.

It is not proposed to develop the expressions in detail, but only to give the results, as they may be readily found in the manner adopted under the last heading with the exception that inasmuch as transference takes place in steps, the accumulated parasitic voltage in any one lamination at the end of partial transference must be found by taking the summation of finite quantities instead of the integration of infinitesimal quantities.

The various terms in the loss factor for the present case are calculated as follows:—

(1) The extra loss factor due to local currents in the bars is calculated from formula (2) or (3).

(2) The extra loss factor due to circulating currents in the $(n-r+1)$ range of laminations is given by the expression

$$\left(\frac{d}{n}\right)^4 b^2c^2(N_1^2-1)\left\{\frac{4N_1^2-1}{45}+\frac{N_1^2(P_1^2-P_1)}{3}\right\}\frac{N_1}{n} \quad . \quad (28)$$

where $N_1=n-r+1$, and $P_1=\dfrac{2n-r+1}{(n-r+1)}+\dfrac{n(p-1)}{n-r+1}$

p being the equivalent value for the coil as derived in the last section.

(3) The extra loss factor due to circulating currents in the $(r-1)$ range of lamination is given by the expression

$$\left(\frac{d}{n}\right)^4 b^2c^2\left(\frac{n-r}{n}\right)^2(N_2^2-1)\left\{\frac{4N_2^2-1}{45}+\frac{N_2^2(P_2^2-P)}{3}\right\}\frac{N_2}{n} \quad (29)$$

where $N_2=r-1$, and $P_2=\dfrac{n+r-1}{2(r-1)}+\dfrac{n(n-r)(p-1)}{r(r-1)}$

p having the same value as before.

(4) The extra loss factor due to circulating currents between the two ranges is given by

$$\left(\frac{d}{n}\right)^4\frac{b^2c^2}{36}(n-r)^2(r-1)(n-r+1) \quad . \quad . \quad (30)$$

Fractional-pitch Windings with Successively Transferred Laminations.

As already pointed out in section 4, there may be certain conductors in the upper layer of a two-layer winding with a fractional pitch which are subjected to external influence of current out of phase with their own. In the case of the type of winding now under consideration, it will be seen that with a fractional pitch, although the cycle of transference is completed mechanically, it is not completed electrically.*

For the sake of example we will consider only a single-turn coil. When other cases arise they can always be first converted into an equivalent conductor, which can then be dealt with in the manner now proposed for the single-turn coil.

Now, in a fractional-pitch winding some of the upper conductors are subjected to an external influence represented by $\cos\phi+j\sin\phi$ instead of by unity. If we express the external influence in the form $1+(\cos\phi-1)+j\sin\phi$, we may then consider the case as if the electrical transference had first been completed, and that then a number of coils (s) had been subjected to an external influence of $(\cos\phi-1)+j\sin\phi$.

By the partial transference of s steps out of n steps, the bottom range of the conductor consisting of $(n-s+1)$ bars is subjected to an equivalent external influence of

$$\binom{n}{n-s+1}(\cos\phi-1+j\sin\phi)$$

and the top range of laminations consisting of $(s-1)$ bars is subjected to the equivalent external influence of

$$\frac{n(n-s)}{s(s-1)}(\cos\phi-1+j\sin\phi)$$

* See, however, some methods described in British Patent 135,533.

Using formula (15) the extra loss factor will be found to be

$$\frac{1}{12}\left(\frac{d}{n}\right)^4 \sin^2\phi/2 \cdot b^2 c^2 \cdot s(n-s)(n s - s^2 + 2) \quad . \quad (31)$$

remembering that although the voltage is derived from the partial transference of s conductors, the current which results has to travel over $2n$ conductors.

In a three-phase machine with a 5/6 pitch, $s = \frac{1}{2} n$ and the expression simplifies to

$$\left(\frac{d}{n}\right)^4 \frac{b^2 c^2 n^2 (n^2 + 8)}{192} \quad . \quad . \quad . \quad . \quad . \quad (32)$$

APPENDIX I.

Complete Synthetic Treatment of Eddy-current Problems.

The synthetic treatment has been applied in the body of the paper so far as to deal with the most practical cases which will arise. In the present appendix the use of this method in the derivation of the complete factors is briefly dealt with.

From the physical discussion of the eddy-current problem as applied to slot conductors on page 280 it will be seen that the derivation of any order of eddy current from the previous order is carried out by the operations indicated by the mathematical symbols

$$\frac{1}{s \times 10^8} \cdot \frac{d}{dt} \frac{4\pi a}{10} \iint f(h, t)\, d h \cdot d h$$

where $f(h, t)$ represents the nature of the previous order.

The operation consists essentially of a double integration of space and a single differentiation in time. Inasmuch as the current variation is assumed to be sinusoidal and may therefore be exhibited in mathematical script by $e^{j p t}$, where $p = 2\pi f$, the differentiation in the above operation will result merely in multiplying the function operated upon by $j p$.

Taking now the case of the first conductor in which, as a result from the applied electromotive force the lowest order of current is a uniform distribution, and taking this uniform distribution as unity it will be readily seen that the complete expression for the current may be written down, apart from boundary conditions, as follows:—

$$1 + \frac{2 j m^2 h^2}{2!} + \frac{4 j^2 m^4 h^4}{4!} + \frac{6 j^3 m^6 h^6}{8!}, \text{ where } m = 2\pi\sqrt{\left(\frac{f a}{10^9}\right)}$$

Remembering that $\cosh x = 1 + \frac{1}{2!} x^2 + \frac{1}{4!} x^4 + \ldots$, it will be observed that the above series, in order to facilitate further manipulation, may be written as

$$\cosh m h\sqrt{(2j)} = \cosh m (1 + j) h$$

Now the boundary conditions in the problem are that the average value of this current must be unity.

This can be arranged by introducing a coefficient which will consist of an infinite series of ascending powers of the constant H, the height of the conductor. Thus, if k be the coefficient, then

$$\frac{1}{H}\int_0^H k \cosh m (1 + j) h = 1$$

whence

$$k = \frac{H m (1 + j)}{\sinh m (1 + j) H}$$

The complete expression for the eddy-current distribution in a bottom conductor is therefore

$$\frac{H m (1 + j) \cosh m (1 + j) h}{\sinh m (1 + j) H} \quad . \quad . \quad . \quad . \quad (33)$$

We will take next the case of a conductor carrying no current of its own, but subjected to the external influence of another conductor of the same depth H and carrying alternating current of unit current density. This is analogous to the problem of the eddy current in an iron plate subjected to external magnetization.

In this case it is the evenly distributed magnetomotive force which is the originating cause of the phenomenon, and again treating it synthetically we may say that this magnetomotive force sets up a series of magnetomotive forces of first, second, etc., orders, in the same manner as in the previous case the evenly distributed current set up a series of eddy currents. In other words, we may look upon the four relations on page 280 as giving rise to a cycle of mathematical operations which may be continued indefinitely. We may enter the cycle at any point and derive a series for the actual physical quantity dealt with at the point of entry.

In the present case the variation of magnetomotive force across the conductor will therefore be given by $(4\pi/10)\ H w \cosh m h (1 + j)$. The boundary conditions in this case are that when $h = 0$ and also when $h = H$, the magnetomotive force $= (4\pi/10)\ H w$.

We may satisfy the double condition by taking the centre of the conductor as the origin of ordinates: then when $h = \pm \frac{1}{2} H$ the magnetomotive force $= (4\pi/10) w H$.

Using k as a series of constant terms in ascending powers of $\frac{1}{2} H$, then obviously $k = \cosh (\frac{1}{2} m H) (1 + j)$, so that the complete function of magnetomotive force is given by

$$\frac{4\pi H w}{10} \cdot \frac{\cosh m h (1 + j)}{\cosh (\frac{1}{2} m H) (1 + j)}$$

whence the current distribution

$$= \frac{(1 + j) m H \sinh m h (1 + j)}{\cosh (\frac{1}{2} m H) (1 + j)} \quad . \quad . \quad . \quad . \quad (34)$$

Graphical Representation of Eddy Currents.

The use of complex hyperbolic functions for expressing eddy-current distribution leads to an interesting method of representing them graphically.

The complex hyperbolic functions $\cosh (1 + j) x$ and $\sinh (1 + j) x$ may be represented in exponentials respectively by

$$\tfrac{1}{2}\left[e^{h (1 + j)} + e^{-h (1 + j)}\right]$$

and

$$\tfrac{1}{2}\left[e^{h (1 + j)} - e^{-h (1 + j)}\right],$$

It is well known that $\frac{1}{2} e^x (1 + j)$ may be represented by a logarithm spiral* as shown in Fig. 18, with an initial value of unity with the radius vector at the zero angular position, and similarly $\frac{1}{2} e^{-x} (1 + j)$ may be represented by the continuation of the spiral in negative angular position and with radius vector continually diminishing below unity.

The value of $\cosh h (1 + j)$ may then be obtained by taking the vector sum of the two radii vectors for angular

* A. E. Kennelly: "Application of Hyperbolic Functions," 2nd edn. p. 71; and C. V. Drysdale, *Electrician*, 1907 8, vol. 60, p. 323.

values $+h$ and $-h$, and similarly sinh $h\,(1+j)$ is the vector difference between the same radii vectors.

The complex hyperbolic functions in Fig. 18 have been constructed in this way. In order to use these diagrams

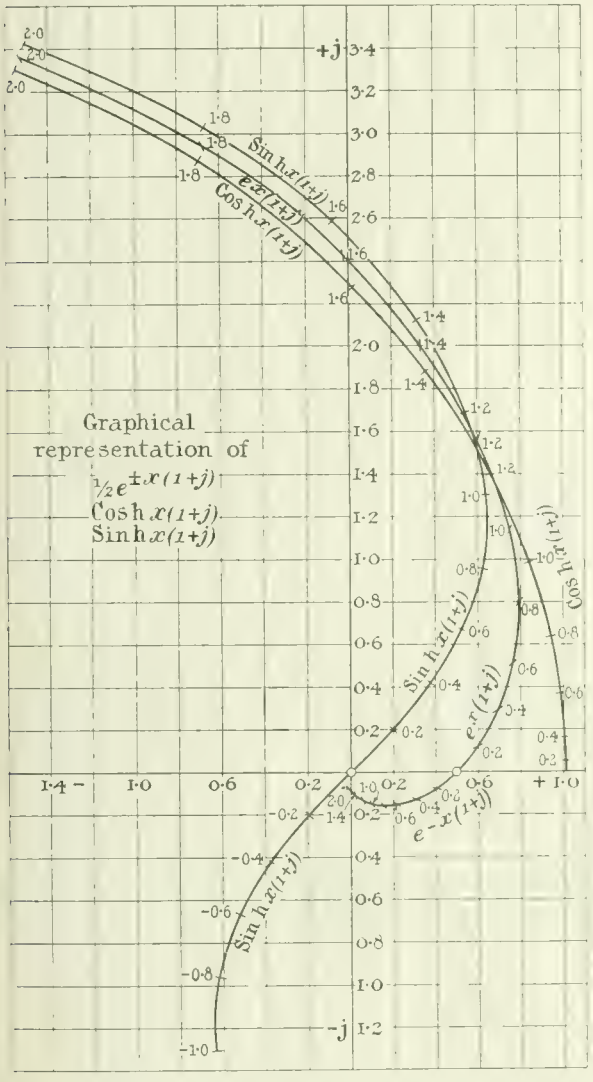


FIG. 18.

to represent the current in, say, a second conductor we proceed as follows:—

(1) Divide the radii of the cosh $h\,(1+j)$ curve within the range of values corresponding to the depth of the conductor by the radius of sinh H $(1+j)$. Then retard their phase by the geometrical angular value of sinh H $(1+j)$.

(2) Divide the radii of the sinh $h\,(1+j)$ curve over half the depth of the conductor by the radius of cosh $\frac{1}{2}$H $(1+j)$ and retard them by the angular value of cosh $\frac{1}{2}$ H $(1+j)$.

(3) Corresponding radii of the curves found in (1) and (2) are then combined to give the complete eddy-current curve for the conductor in question.

To obtain absolute magnitude and direction the radii vectors must further be multiplied by H $m\,(1+j)$.

An example is given in Fig. 19 in which the depth of the conductor is such as to give 2 as the value of H. This corresponds to a copper conductor at 100° C. occupying the full width of the slot of a depth of approximately 0·84 inch, the frequency being 50.

If the resultant curve is then placed in successive angular positions, and if from each position each radius is projected on to ordinates corresponding to its position in the depth of the conductor, we may obtain a representation of the variation of the current in the various laminæ throughout the cycle.

Such a set of cinematograph diagrams has been supplied in Fig. 20 to represent current distribution in a copper conductor approximately 2 cm. deep at frequency 50 at 18 successive stages during half of a complete period. The conductor is approximately the same as that for which Fig. 19 is drawn.

The height of the conductor is represented horizontally and the current distribution vertically.

The top series of diagrams represents the current distribution in a bottom conductor, the second series of induced diagrams represents current induced in the second conductor by the current in the first, and the bottom series of diagrams represents a combination of the previous two series, that is, it represents the current distribution in the second conductor when carrying current.

The mean value of the current, that is, the fundamental current, is also indicated at each stage. The bottom of the slot is on the left-hand side of each diagram.

IMPEDANCE OF ALTERNATING-CURRENT CONDUCTORS IN SLOTS.

The eddy-current distributions expressed as above enable us quickly to derive an expression for the impedance factors of the conductors, i.e. for the impedance in terms of the resistance to direct current.

From formula (33) we observe that the current in the topmost laminæ of the bottom conductor is given by

$$\frac{\mathrm{H}\,m\,(1+j)\cosh m\,(1+j)\,\mathrm{H}}{\sinh m\,(1+j)\,\mathrm{H}}$$

$$= \mathrm{H}\,m\,(1+j)\coth (1+j)\,\mathrm{H} \quad . \quad . \quad . \quad (35)$$

As this current is inductionless with regard to the rest of the conductor, this expression also represents the ratio of voltage necessary to send the current from the conductor as compared with the voltage necessary to send the same current through a conductor which has only resistance. It is therefore the impedance factor of the conductor.

Reducing formula (35) to a single complex expression, we have by simple trigonometry

$$m\mathrm{H}\left[\frac{(\sinh 2m\mathrm{H}+\sin 2m\mathrm{H})+j\,\sinh 2m\mathrm{H}-\sin 2m\mathrm{H}}{\cosh 2m\mathrm{H}-\cos 2mh}\right] \quad (36)$$

The real portion of this expression is the resistance factor or the loss factor of Field; the imaginary portion is the reactance factor.

Turning now to the case of a dead conductor, placed above the bottom conductor and externally magnetized by

it, the current in the topmost lamina is from (34) given by

$$m\,\mathrm{H}\,(1+j)\tanh\tfrac{1}{2}\,m\,\mathrm{H}\,(1+j) \quad . \quad . \quad . \quad (37)$$

The current also flows in the opposite direction along the bottom of the conductor, and is a measure of the

In the form of a single complex expression this additional impedance factor is found to be

$$2m\mathrm{H}\left[\frac{(\sinh m\mathrm{H}-\sin m\mathrm{H})+j(\sinh m\mathrm{H}+\sin m\mathrm{H})}{\cosh m\,\mathrm{H}+\cos m\mathrm{H}}\right] \quad (38)$$

The real portion of this expression again corresponds to

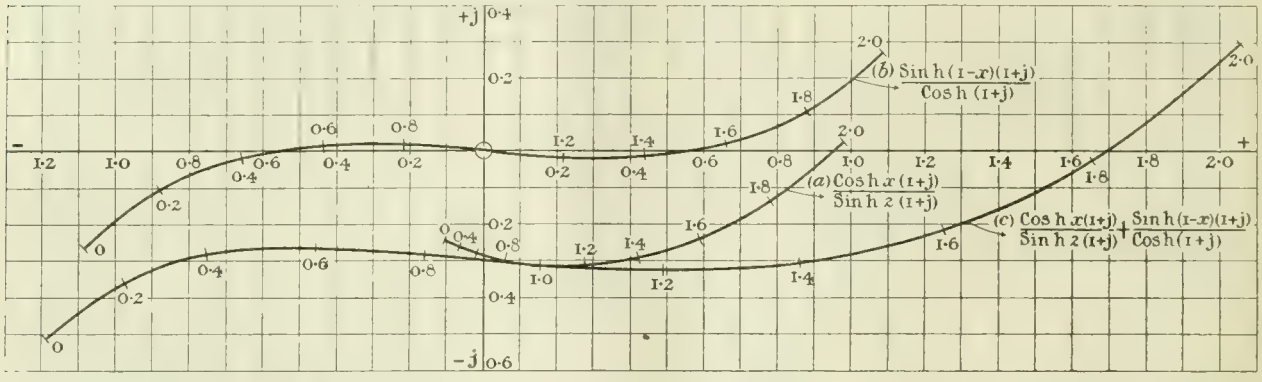


FIG. 19.—Graphical vectorial representation of eddy currents in first and second conductors (copper at 100° C.). Height of conductor = 0·84 in., occupying the whole width of the slot.

(*a*) Current in first conductor.
(*b*) Current in second conductor due to first conductor.
(*c*) Combined currents in second conductor.

Various equidistant positions in conductors from the bottom are marked upon the curves.

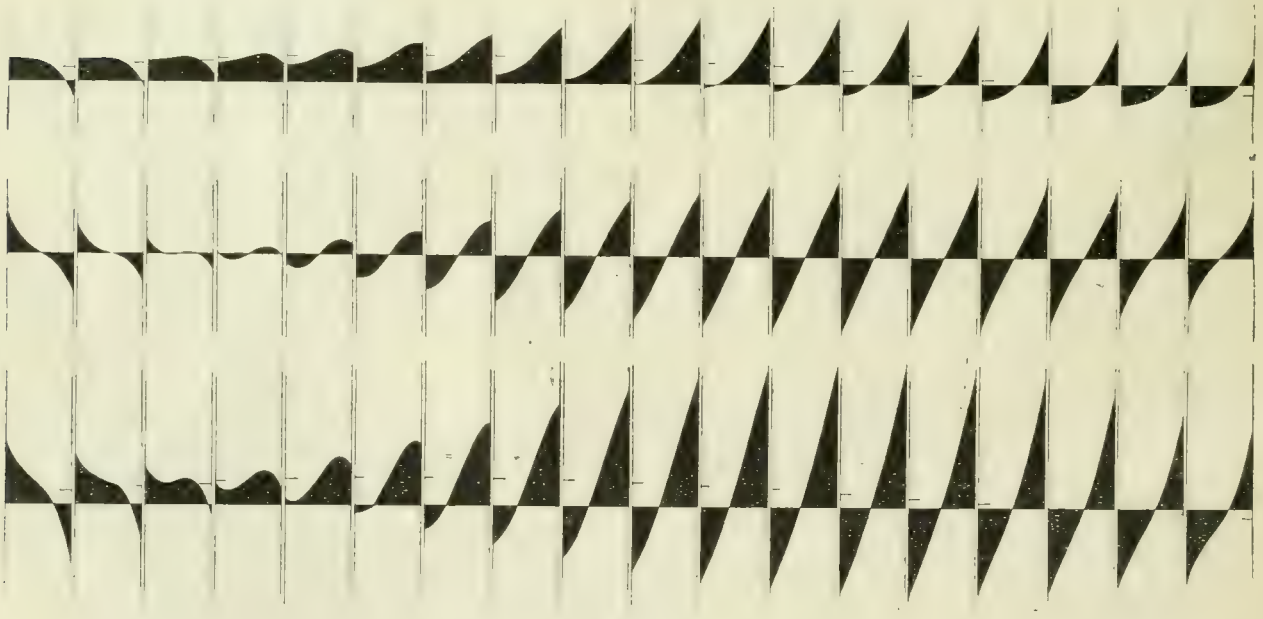


FIG. 20.

voltage generated between the outermost laminæ of the conductor by the flux across the conductor. This flux also links the bottom conductor as a whole, and expression (5) multiplied by 2 therefore corresponds to an additional impedance factor to the bottom conductor, although the loss corresponding to the real portion of it occurs in the upper conductor.

Field's term for loss factor in an externally magnetized conductor.

Considering now the case where the second conductor is also carrying the main current, the current in the topmost laminæ is

$$\mathrm{H}\,m\,(1+j)\,[\coth m\,\mathrm{H}\,(1+j)+\tanh\quad m\,\mathrm{H}\,(1+j)]$$

and the voltage for the main current in this conductor may be expressed as an impedance factor in this form.

The voltage necessary to drive the current through the second conductor is, however, not in phase with the voltage necessary to drive the current through the first

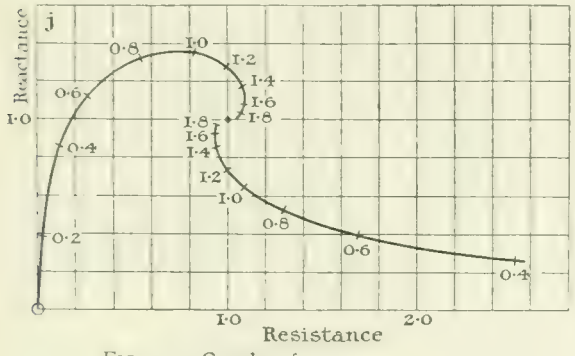


FIG. 21.—Graphs of :—

(a) $(1+j)\tanh m\,H\,(1+j)$.
(b) $(1+j)\coth m\,H\,(1+j)$.

Values of m H are indicated on the curves.

conductor, by reason of the flux which passes across the second conductor and links the first conductor as a whole. This voltage arises firstly from the flux created by the external magnetization of the first conductor, which we have just seen corresponds to an impedance factor of $2\,m\,H\,(1+j)\,\tanh\frac{1}{2}m\,H\,(1+j)$, and secondly from the

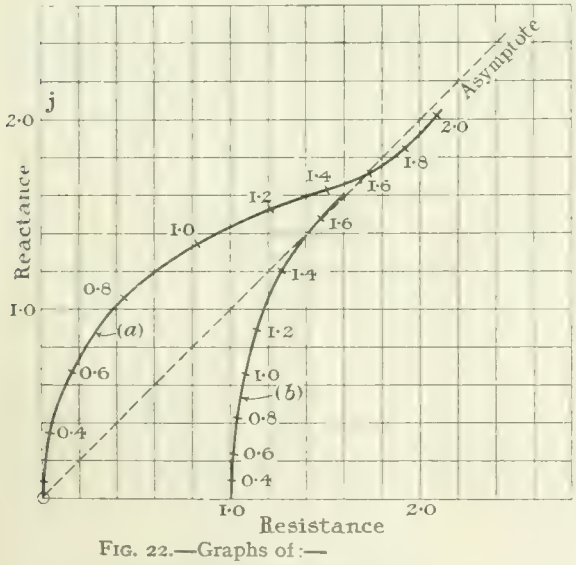


FIG. 22.—Graphs of :—

(a) $m\,H\,(1+j)\tanh m\,H\,(1+j)$.
(b) $m\,H\,(1+j)\coth m\,H\,(1+j)$.

Values of m H are indicated on the curves.

flux created by the second conductor's own current. The measure of this is the difference in the voltage required to pass this current through the topmost and the bottommost laminæ of the bottom conductor which is, in the form of an impedance factor,

$$\frac{H m(1+j)\,[\cosh m\,(1+j)H - 1]}{\sinh m\,(1+j)\,H} = H m(1+j)\tanh m\,(1+j)\tfrac{1}{2}H$$

The voltage, both in phase and in magnitude with reference to that for an inductionless bottom conductor, to send current through the second conductor is therefore

$$H\,m(1+j)\,[\coth m\,H\,(1+j) + 4\tanh\tfrac{1}{2}m\,H\,(1+j)]$$

The real portions of this expression indicate the heat loss in the second conductor.

More generally in the case of the pth conductor, it may be shown by similar argument that the factor for the hyperbolic tangent term is $2\,(p^2-p)$.

A graphical representation of complex hyperbolic tangent and cotangent may be readily developed from the complex hyperbolic cosines and sines in the previous pages.

Fig. 21 shows these functions multiplied by $(1+j)$, and Fig. 22 shows a complete graphical development of the terms in the impedance factor expressions. The first figure indicates at a constant frequency the variation of impedance with a varying depth of conductor—the impedance tends to a constant value whatever the depth—and the second curve indicates the variation of impedance for a given depth of conductor with varying frequency.

An interesting feature brought out by these curves is that with deep conductors the resistance and reactance attain the same value.

For practical use the real and imaginary portions of expressions (35) and (37) are best plotted out separately in ordinary Cartesian co-ordinates, with m H as the independent variable.

APPENDIX II.

Losses in Conductors of such Irregular Shapes as are not Amenable to Mathematical Representation.

The similarity between eddy current and transmission-line problems has already been discussed by Hay * and by Howe.†

The student will not have failed to have further noted this similarity in perusing the previous appendix. It is our present purpose to show how the approximate calculation of irregularly shaped conductors may be expeditiously carried out by developing and calculating step by step an equivalent transmission line from a knowledge of the mechanical shape and dimensions of the conductor.

The distinctive feature of such an hypothetical transmission line is that the line itself contains only reactance and the leakage from it consists of pure resistance. In the usual case of a rectangular conductor the distribution of this inductance and leakage resistance is uniform, but in the special case now being considered the distribution varies in a manner depending upon the shape of the conductor.

The method can be best explained by an example. In Fig. 23 is shown the section of a wedge such as is used to retain the rotor windings in the slot of a turbo-alternator. In a machine designed for single-phase working the wedge serves the further purpose of carrying currents of double frequency to compensate for the armature reaction, and in this connection it is necessary to know the equivalent resistance of the wedge at this frequency.

* *Journal I.E.E.*, 1911, vol. 46, p. 487.
† *Ibid.*, 1916, vol. 54, p. 473.

The first step is to divide the conductor into a suitable number of strips, say 10, and then to tabulate the resistance of each strip and the reactance to which the flux across each strip gives rise. The strips need not all be of the same

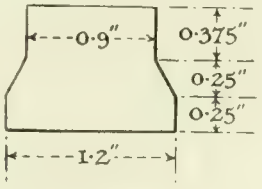


FIG. 23.

height, but for the present example it is most convenient to arrange them so.

The resistance of the strip is given by $\frac{\rho}{w\,h}$, and the reactance by $2\pi f(4\pi/10^9)\,h/w$, where $w =$ width of the strip and $h =$ its height.

The following tabulation applies to the present example when the frequency is 100 cycles per second.

The next step is to draw a transmission-line diagram at the bottom of the conductors has been taken as unity and the other figures have been varied in proportion.

Assuming unit voltage at the far end of the line corresponding to the bottom of the conductor, the currents and voltages at the different points along the line can be built up step by step, with the result that the wedge as used for carrying 100-cycle current has 3·3 times the resistance it would offer to direct current.

No. of strip	h (cm.)	x (cm.)	Resistance ohms × 10^6	Reactance ohms × 10^6
1	0·222	3·05	3·39	0·575
2	0·222	3·05	3·39	0·575
3	0·222	3·05	3·39	0·575
4	0·222	2·87	3·60	0·611
5	0·222	2·59	3·99	0·675
6	0·222	2·36	4·38	0·742
7	0·222	2·28	4·53	0·766
8	0·222	2·28	4·53	0·766
9	0·222	2·28	4·53	0·766
10	0·222	2·28	4·53	0·766

Total current in section of line	-1·550+j2·895	-0·470+j2·403	0·204+j1·832	0·569+j1·295	0·716+j0·855	0·723+j0·521	0·642+j0·277	0·505+j0·115	0·34+j0·029	0·17+j0
Current in leak	-1·08+j0·492	-0·674+j0·571	-0·365+j0·537	-0·147+j0·440	0·007+j0·334	0·081+j0·244	1·37+j0·162	0·165+j0·086	0·17+j0·02	0·17+j0
Reactance of line element (ohms)	j1·332	j1·332	j1·332	j1·332	j1·292	j1·175	j1·064	j1·0	j1·0	j1·0
Resistance of leak (ohms)	7·88	7·88	7·88	7·88	7·63	6·95	6·26	5·5	5·9	5·9
Voltage drop in section of line	-3·20+j0·626	-2·440+j0·272	-1·725+j0·758	-1·105+j0·925	-0·612+j0·85	-0·295+j0·683	-0·115+j0·505	-0·029+j0·34	0+j0·17	
Total voltage at head of leak	-8·521+j3·877	-5·321+j4·503	-2·881+j4·231	-1·156+j3·473	-0·051+j2·548	0·561+j1·698	0·856+j0·015	0·971+j0·510	1·0+j0·17	1·0+j0
Resistance of line to head of leak	2·267	2·22	2·105	1·92	1·72	1·62	1·70	2·04	2·95	5·9
Corresponding resistance for direct current	0·69	0·755	0·835	0·933	1·06	1·23	1·5	1·97	2·95	5·9
Total loss factor	3·29	2·94	2·52	2·06	1·62	1·316	1·133	1·035	1·0	1·0

FIG. 24.

as in Fig. 24 from the resistances and reactances just tabulated. It sometimes facilitates the subsequent arithmetic if the resistance or reactance at one end of the table is made equal to unity. In the figure the reactance figure

The full calculation has been given in Fig. 24.

In conclusion the author wishes to thank the British Thomson-Houston Co. for permission to use examples from their turbo-alternator practice to illustrate his paper.

DISCUSSION BEFORE THE SOUTH MIDLAND CENTRE, AT BIRMINGHAM, 7 JANUARY, 1920.

Mr. F. H. Clough: With increase in the sizes of electrical machinery, especially turbo-alternators, the size of slot has grown very much, and it has become necessary to understand fully the causes which produce additional losses in the copper conductors, so that suitable means may be adopted to avoid these losses. The author has attacked the problem from a physical aspect, and has used mathematics only as a means of

solving the physical problems. In doing this he has been able to simplify the mathematical part of the problem and produce a method whereby practically all types of windings can be calculated comparatively simply. The paper marks a distinct progress in the design of electrical machinery.

Dr. M. Kahn : By considering only the eddy currents of the first order the author has explained the whole matter in a comparatively simple manner. To neglect the eddy currents of higher order is certainly justified, as an approximate knowledge of the increase in the copper losses is all that is required. In considering the losses in conductors built up of a number of laminations connected solidly together at the ends, the author states that the extra loss factor in the case of an infinitely laminated conductor is reduced by the square of the ratio of the core length to the total length of the conductor. This seems to be scarcely correct, since it ignores the fact that the losses in the part of the conductor outside the slot are increased owing to the laminations. In the case of a solid conductor the alternating current in the end winding is practically uniformly distributed over the whole conductor and the copper loss therefore equals the loss which would take place with an equivalent direct current. If the conductor is laminated and the laminations are so insulated that no current can pass from one to another, the losses per unit of length in the external part of the conductor and in the part of it within the slot must be equal. Although the loss in the embedded portion is reduced in the ratio of b^2 by laminating the conductor, the total loss is only reduced in the ratio of b, compared with a solid conductor If u is the loss per unit length corresponding to direct current, l the length of the core, and L half the length of one turn, then

$$(1+K)\,l\,u + (L-l)\,u = (L+K\,l)\,u$$

is the loss in a half turn of a solid conductor, and

$$(1+K\,l^2/L^2)\,L\,u = (L+K\,l^2/L)\,u = (L+b\,K\,l)\,u$$

is the loss in a half turn of the laminated conductor. It would be of interest if the author would explain whether it is necessary to insulate the sections of laminated or stranded conductors. In the case of stranded conductors, where the strands are arranged in spirals the voltage between the various strands is very small, as each strand changes its position continuously and completes a full cycle of transposition in each pitch of the spiral. The resulting voltage between strands is smaller than the voltage drop necessary in order that current may flow through the surface contacts between the various strands. In the case of a laminated conductor where the laminations are joined at the end of each half turn, the voltage between the laminations is higher. Even so the surface drop may still reduce the currents flowing between laminations in the end winding to negligible amounts if the number of laminations is large. If the number of laminations is small, or if the ends of the laminations are not joined up each half turn, insulation is of course essential. Fig. 7 gives most useful information regarding the number of laminations necessary to reduce the loss, and it appears that for an average case a sub-division of the conductors in three layers is sufficient; the layers would of course have to be insulated. A further sub-division does not affect the losses materially. In Appendix II the problem of the current distribution in bars of the damping winding of single-phase turbo-alternators is investigated. This case differs from the general case in so far as the bars in question are located in the top of the slot in which another winding is placed. This winding, the field winding, can be considered as short-circuited, and the flux variations interlocked with it are damped out by the currents which they induce in this short-circuited winding. It is doubtful whether the method of calculation used in the paper can be applied to the case in point without taking the influence of the field winding into account. If this influence is excluded, the flux taken into consideration must not be interlocked with the field winding, but must recross the top of the slot above this winding. The reluctance of the path of this flux is therefore proportionate to double the slot width $2w$, while in the author's calculations only w is introduced.

Mr. W. M. Cranston : The author brings forward one or two methods of crossing over laminations in conductors and thereby eliminating to a large extent the eddy-current loss. That this is of great importance may readily be appreciated when one considers that the only alternative at present available is the adoption of a completely stranded conductor. The stranded conductor to reach its maximum efficiency should have its strands completely insulated throughout the whole of its embedded length, and should have such a pitch that a multiple of the pitch will exactly coincide with the length of the iron core. In normal practice neither of these features is completely obtained. But the resultant loss is usually so small that it will be found to be less than the eddy-current loss in the individual laminations of the interconnected conductor. The stranded conductor, however, costs about 50 per cent more than a solid bar of the same dimensions. In large machines this economy will go a long way towards paying for the extra connections and, in spite of the increased risk of breakdown due to the multiplication of connections, may induce manufacturers to adopt the system shown. In smaller machines we are content to suffer the inconvenience of eddy currents. Designers are, however, apt to attach too great importance to the depth of copper for minimum loss. The section of the paper relating to the depth of copper required for minimum intensity of heat dissipation contains valuable figures. These show that the depth of copper may under certain conditions be increased by about 30 per cent with advantage to the machine. Of course the losses in the slots are increased; but the gain on the overhang may more than compensate for that and we may get a more efficient and cooler machine. In certain cases even this depth may be exceeded with impunity.

Mr. N. Shuttleworth : This paper treats of a very specialized subject, but it will certainly receive the commendation of all those engineers for whom it has interest. The analysis of eddy-current problems has been attempted in a very novel and clear way, and the application of the results so obtained has had and will continue to have considerable influence on the develop-

ment of large machines. What has remained for some time in the past a matter for designing instinct, has now been reduced to determination by simple algebra. To know in the first place exactly what the copper losses in a machine are going to be, enables the designer to increase the current volume carried per unit length of the periphery of the air gap to the highest possible value, which means a considerable increase in the safe rating of the machine. It is conceivable that the eddy-current losses may be so much reduced by suitable design that the current volume which can be carried by the stator is no longer a limiting feature; the relation which exists between the current volumes on stators and rotors is well known and it is of interest to note the trend of development in the past few years in this respect. It will be found that the copper section on a modern rotor for an alternator is double that on a rotor of the same diameter built 10 years ago; this can be explained in several ways: (1) There was undoubtedly an initial conservatism in design; (2) considerable improvement in ventilating arrangements has been possible; (3) the stator has been able to carry more and more current volume as means for reducing the eddy-current losses has been found. It is evident, however, that this process cannot continue indefinitely; to increase the copper section on a rotor reduces the available magnetic section, so there must be certain proportions for which the output is a maximum. I examined this some time ago and arrived at the following conclusions: in order to obtain maximum output from a rotor, the slot depth should be one-eighth of the rotor diameter, and the width of the tooth at the root should be one-half of the active copper width in the slot. Of course, small deviations from these proportions in a rotor will not appreciably affect the output. Now the diagrams which the author has shown approximate very closely to these results, hence we may conclude that present-day rotors have reached proportions which cannot be materially improved. Perhaps one might be inclined to assume that eddy currents are not of great importance if the rotor is the limiting feature in a design and there is no need to worry unduly about them, but the author might assure us that it is only by reducing eddy-current losses that the limit has been forced from the stator to the rotor. In any case, it would be of interest if the author would indicate what other means there are at our disposal for still further increasing the output of a machine of given size other than by improving the ventilating arrangements.

Mr. H. W. Taylor (*in reply*): With reference to Dr. Kahn's first point, I should explain that throughout the paper all comparisons of loss factors have reference to the slot portion of the conductors, as in most cases it is the intensity of the losses in these positions and not the total losses in the machine which are important. On this basis the statement in the paper is correct, but it is of course recognized that reduction in the eddy-current losses in the slot portion by lamination is accompanied by an increase in the loss in the hitherto "eddy-currentless" end portions. When the laminations are of finite thickness the extra loss factor for the end portions is that part (K_0) of the combined loss factors which is due to circulating eddy currents. In reply to Dr. Kahn's second point, it is necessary to insulate the laminations from one another, although this insulation need only amount to a mechanical separation. With regard to Fig. 7, it must be understood that this has only been drawn for a particular case. Similar diagrams drawn for deeper conductors will show that finer lamination is required if the losses are to be reduced in the same proportion.

I am afraid I cannot accept Dr. Kahn's criticism of the application of the graphical method to the calculation of the loss factor in the squirrel-cage bar. I regard the squirrel-cage bars and the exciting winding below them as associated together like the multiple strips of a laminated conductor, but with the distinction that the lower strips in this case have greater resistance than the top one. Therefore the imaginary local flux path after traversing the bar will pass down one side of the slot to the bottom, and up the other side. Objection might, however, be taken to calculating an irregular conductor in the way suggested, as flux enters such a conductor normally at all surfaces, but in the present case I do not think any large error will occur through assuming that the flux passes everywhere straight across the conductor from one side of the slot to the other.

Mr. Shuttleworth discusses a number of points in design associated with eddy currents.* It certainly appeared a few years ago that the limit in design would be in the stator, due to eddy currents generated in the windings. The difficulties associated with these have now been overcome, and we must look for further progress in improved methods of cooling and in the more scientific use of heat-resisting insulating materials.

In conclusion I add two supplementary formulæ to (31) and (32) in the paper. These last relate to the losses which arise with fractional pitch windings, when the cycle of transference is completed over one pole. In many cases a cycle of transference occupies several poles, and the upper conductors subjected to the influence of another phase are then distributed in a number of small ranges throughout the cycle. In such a case formulæ (31) and (32) give place to:—

$$\frac{1}{12\,P^2}\left(\frac{d}{n}\right)^4 \sin^2(\phi\ 2)\,.\,b^2 c^2 s(n-s)(n\,s-s^2+2\,P^2)\,. \quad (39)$$

and

$$\left(\frac{d}{n}\right)^4 \frac{b^2 c^2 n^2 (n^2+8\,P^2)}{192\,P^2} \quad . \quad . \quad . \quad (40)$$

if P in this case is the number of poles over which the cycle of transference is distributed.

* The diagram referred to by him was shown at the meeting when this paper was read and is included in my contribution to the discussion of Mr. Shepherd's paper (see page 148).

DISCUSSION ON

"TRANSFORMERS FOR ELECTRIC FURNACES."*

SCOTTISH CENTRE, AT GLASGOW, 10 FEBRUARY, 1920.

Mr. R. B. Mitchell: This paper contains much very useful information which is being eagerly sought after in this district. It seems to me that the introduction of reactance is most important and essential in the case of transformers for furnace work. When we think of the great forces let loose if a short-circuit should take place—and short-circuits are most likely in the furnace—the necessity of reactance is at once seen. In comparing frequencies of 25 and 50 for furnace work there is, I understand, a considerable difference in the cost of the transformer in favour of the higher frequency. High-tension tappings have always been a source of weakness and I dare say would have been discarded ere this if there had been no extra cost involved in the provision of regulating apparatus. I am certain that in spite of the extra cost these appliances will ultimately be adopted. I accept the author's statement that units of 8,000 k.v.a. capacity are probable in the future, and I trust that, in Glasgow at all events, furnaces of that capacity will not be located very far from the power station. It is another argument in favour of transmission cables at much higher pressures than 20,000 volts. In this connection, does the author think it advisable to concentrate 8,000 k.v.a. in one unit; and what, if any, are the disadvantages in not doing so? Scott connections are referred to in the paper. In the Glasgow area there is a Scott-connected transformer for furnace work, but I have not heard that there has been any trouble due to the connections. The author explains the advantages and disadvantages of the core type and the shell type for furnace work. In the case of ordinary power transformers one usually prefers the core type on account of the accessibility of the coils. The author seems to work out a case for the shell type. Has he any data as to the actual performances of these two types? The extremely practical advice given as to the proper lay-out of these transformers is of great value and will be highly appreciated by those who have or may have anything to do with the work of electric furnaces.

Mr. L. E. Wood: I was an interested spectator at the dismantling of one of two furnace transformers that had been in use for about two years. One of these two had previously broken down and it was decided to dismantle the other for the purpose of ascertaining its condition and, if possible, gathering information as to the cause of breakdown of the first. On opening out the transformer it was found that the insulation of the inner portion of the winding was very brittle and in some places charred. This showed that the middle portion had developed a high temperature rise, which is the governing feature of the useful life of a furnace transformer. It was also noticed that a large amount of sludging had been taking place. It is suggested that the more liberal use of separators providing a larger cooling surface would materially lengthen the life of the insulation. The use of an "oil conservator" is stated to eliminate oil decomposition or sludging, also "breathing," thus conserving the insulating value of the oil.

Mr. A. P. Robertson: The author has not dealt very fully with transformers for resistance furnaces, and I think he has done wisely, as there is enough matter for a paper in the study of transformers for arc furnaces. The conditions are much more severe in the latter due to the short-circuits when the arc is struck. One of the reasons that the conditions are so severe at this time is that the mechanism for moving the carbons is too slow. In any furnace which I have seen the arc is struck by hand and, although it may be only a second or so before the carbons are separated, this gives time for very severe stress on the transformer. If the carbons were to stick together, the transformer might be seriously damaged unless the protection on the high-tension oil-break switch is very positive. The contacts of this switch require a good deal of attention as the switch operates very frequently and the contacts should be of heavy butt type. The arcing tips should be extra heavy and easily renewable. With regard to the high-tension selector switches, these are often air-break switches, which necessitates the use of copper rod between the switches and the transformer terminals. It is not a safe job, and I believe that in more recent jobs oil-immersed selector switches are used and solid conductors run between these and the transformer. All this tends to safety and continuity of supply. The bracing of the low-tension leads must be very strong to prevent them going together. During the time when the arc is being struck, the low-tension leads vibrate very much. The flexible leads coming down to the carbons (which may be anything in number from 6 to 12) are pulled close together and become rigid. The current during this time is very high, and is generally beyond the compass of the ammeter. As the current falls the leads lose their cohesion and become flexible again. This occurs every time the arc is struck, and there is no doubt that unless the bracing and clamps of the low-tension coils inside the transformer are a strong job, the coils are liable to be damaged. The author mentioned that there is a probability in the near future of larger units, say 8,000 k.v.a. I think the transformer makers should keep in view the weights of these transformers. If necessary, they might be made in two or three smaller units worked in parallel. It is not always easy to move large weights and the transformer houses are not always very roomy. Any weight above 10 to 12 tons is difficult to handle except by mechanical means, as men cannot handle heavy chain blocks above this weight. Although the trans-

* Paper by Mr. J. L. Thompson (see page 201).

formers are not likely to be moved once they are in position, if any repairs have to be done the easier the units are to handle the less time will be spent in repairs. To install a power crane for this purpose would be to tie up a great amount of capital for very occasional use.

Mr. W. J. Cooper : I am interested in a breakdown which occurred on three occasions at the end of the melting period. I wish the author could suggest any possible error in operation which might cause such a breakdown, or any condition in the transformer at that period of the melt which would give rise to special stresses. The furnace in question was of the arc type with hand-operated electrodes.

Mr. G. M. S. Sichel : There are one or two points on which I should like to ask the author's opinion. First, how does the regulation of these special transformers compare with that of the ordinary industrial transformer operating at normal voltages ? The regulation will, of course, depend on the power factor of the circuit, but for the purpose of comparison let us assume similar conditions. Second, I am particularly interested in the author's statement that the low-tension heavy-current winding consists of bare conductors, because I remember a paper read before the Institution some four or five years ago which dealt with the formation of sludge in transformers and in which it was stated that there was a much greater tendency for sludge to form on bare copper conductors than on conductors having a covering of insulation, and that it would appear desirable for the heavy-current secondary winding to be covered with, say, a single layer of tape in order to prevent the formation of sludge. The tendency to sludge is, we know, aggravated if the temperature at which the transformer is operating is high, and it is reasonable to expect higher temperatures on transformers working in proximity to furnaces than in transformers working under usual industrial conditions. Next, with regard to the protective gear required for furnace transformers, in all wiring diagrams showing the lay-out of furnace transformers the only protection provided appears to be that afforded by the use of an ordinary time-limit fuse or fuses which shunt the oil-switch trip coils. As the behaviour of time-limit fuses does not, in general, give by any means constant results, I should be interested to know whether the practice of protecting furnace transformers with time-limit fuses has, in the past, been found to be satisfactory, more particularly bearing in mind the extremely violent and frequent fluctuations of the current during the melting period. The special arrangement of the low-tension heavy-current leads, in order to secure satisfactory operation, is very interesting, as it emphasizes in an interesting manner the well-known fact that if we have a piece of apparatus, of a certain size, operating satisfactorily, we cannot multiply all the dimensions by 10 and then expect the results to be proportionally good. The problem of dealing with conductors carrying 1,000 to 2,000 amperes is a simple one, but when the current to be dealt with runs into tens of thousands, we cannot solve the problem by simply increasing the cross-sectional area of the conductors. The factor of self-induction, which may be negligible when dealing with small currents, becomes of such importance when dealing with very large currents, that it easily may completely outweigh almost all other considerations. I note that the author states there is a limit to the size of the furnace transformers that can be built, and it would appear, therefore, that if provision has to be made for dealing with a very large output from furnace transformers, it would be necessary to have several banks of transformers with their own furnaces. I should like the author to state what would be the best lay-out for electrical furnaces and transformers to deal with a large output, more particularly with regard to the disturbance which would be caused to the supply mains if several banks of furnace transformers were to be switched in simultaneously. Even if some kind of electrical interlock could be arranged between the oil switches controlling the various banks of transformers, there always appears to be a danger of current-rushes taking place simultaneously in several banks of transformers during the melting period, when the current fluctuates very considerably. The same effect on the supply mains would be produced by furnace transformers in different works in the same district switching in simultaneously, and the effect on the supply mains and generating plant may be so serious as even to be disastrous.

Mr. A. E. McColl : One or two speakers have mentioned the sludging of oil in furnace transformers. In the discussion on Dr. Michie's paper * I remember that one of the speakers specially referred to the rapid sludging of the oil in a transformer employed for furnace work. These transformers have a considerable hot copper surface exposed to the oil and I do not know if it has been satisfactorily proved that the sludging is due to this exposed copper surface. The author perhaps may be able to give some information on this point.

Mr. J. L. Thompson (*in reply*) : The introduction of reactance in the electrical circuit of a furnace equipment is, as the author states in the paper, essential, and with this Mr. Mitchell is in agreement. In the case of large installations, as the author has pointed out, reactance is the controlling factor and also the permissible mechanical forces brought into being on a short-circuit are only of moderate value due to the reactance, but nevertheless dangerous due to their frequent occurrence. The cost of electrical apparatus for low frequencies is of a necessity more expensive than that for high frequencies, with the exception of switchgear. This increase in cost is roughly inversely proportional to the frequency, but the curves in Figs. 9 and 10 in the paper give the proportion more accurately. Mr. Mitchell is evidently in agreement with the author as regards tappings and their weakness. With reference to the 8,000 k.v.a. unit suggested in the paper, the author would not recommend a single three-phase unit, but a unit consisting of three single-phase transformers. This would facilitate handling, provision of spares, and give more latitude as regards location. If Mr. Mitchell refers to the author's remarks in his reply to Mr. Cowie at the London discussion (page 214) with

* *Journal I.E.E.*, 1913, vol. 51, p. 213.

regard to the performance of core-type and shell-type transformers, I think he will find his query answered.

Mr. Wood's experience gathered from the dismantling of broken-down furnace transformers would possibly be interesting, but conclusions as to cause of failure may have been entirely wrong, unless he was fully familiar with all details of their standard design and history. As has been stated by many speakers, this type of transformer was often called upon to carry much heavier loads than they were designed for, due to the heavy demand for steel during the war and the inefficient and scant attention given to such plant. The author has had very little, if any, complaints of sludging of oil in shell-type transformers, but if it does occur, this is due to inferior oil or to excessive temperature on account of excessive loading.

In reply to Mr. Robertson, as stated in the paper, transformers for resistance furnaces are similar to those for arc furnaces with the exception of reactance requirements. In any electrical apparatus subject to faults on the system or circuit to which it is connected, the switchgear should be very positive in action. The suggestion that selector switches should be oil immersed is good and safe, but their introduction is generally a question of cost. As the voltages in vogue in this country are of only medium value, the necessity of oil switches for selector gear is a debatable point. If their location is in a damp or very dirty atmosphere, oil-immersed switches would be advantageous, but as they are never operated when under load, they are not necessary for operating only. Loose multiple cables carrying alternating current in the same direction will certainly attract one another and move if free to do so when carrying heavy currents. The question of the 8,000 k.v.a. unit has already been dealt with in reply to other speakers.

In reply to Mr. Cooper the author sees no reason why transformers should be more liable to failure at the end of a melting period than at any other stage of production. The severest strain is always present during the initial stages of the melting period.

With reference to Mr. Sichel's remarks, the regulation of any transformer depends on the power factor of the load, the reactance drop, and the resistance drop of the transformer. With the exception that the power factor is variable during production and the reactance is of fairly high value and varies with the different voltages, the regulation is similar to that of power transformers. It may be 4 or 5 per cent, but a definite value or figure cannot be given due to the above variations. Bare copper tends to sludge oil at high temperatures, but if tinned or taped that tendency is reduced and eliminated with good oil and a reasonable working temperature. As far as the author is aware, time-limit fuses with overload trip coils have given satisfaction. The author does not state that there is a limit to the size of furnace transformer which can be built, but that experience and investigation tends to the possibility of a limit for the size of an electric furnace that can be operated at a reasonable power factor and efficiency. Space and time will not permit of detailing any lay-out schemes, but if the suggestions outlined in the paper be followed a satisfactory lay-out should result. If a bank of furnaces are installed, their starting times are generally staggered, so as to equalize the load and utilize the available labour to the full. Several installations on the same feeder will possibly cause surges on the line, and these surges will be most severe at the dead end of the line, hence a ring main would suggest itself as most suitable for this type of installation.

Mr. McColl also refers to bare conductors causing oil to sludge. This question has already been dealt with, but in the author's opinion it is dependent on the quality of oil and the temperature attained under the worst conditions.

South Midland Centre, at Birmingham, 25 February, 1920.

Mr. A. M. Taylor: The author alludes on page 202 of the paper to the tappings being put in the middle of the winding to eliminate high voltages by the auto-transformer effect, and also to free the reinforced turns from any break in their insulation. It is not quite clear whether the effect in these dead turns is more (per turn) than that in the live turns. Will the author please explain, preferably with a diagram, exactly the arrangement of the tappings and what is the advantage of his arrangement. Nowhere in the paper is the use of three-phase transformers contemplated. Presumably the difficulties in their construction are too great to be faced, in conjunction with the large number of tappings required in the primary, and of parallel coils and their connections in the secondary; but, from the central station engineer's point of view, is not a considerable amount of unbalancing of the mains thereby introduced? On page 205 the author brings out very clearly the losses introduced in the core clamping plates, and shows how this is due to the leakage flux between the sandwiched coils on the core type of transformer, rather inferring that the core transformer is on that account not so good as the shell transformer. This leakage flux could probably be considerably reduced if the coils were subdivided into narrower and deeper coils, thus giving the leakage paths further to travel. This would also get over the difficulty, alluded to on page 205, of the secondary coils sharing the load unequally when certain of the primary coils are cut out of circuit. No doubt the difficulty is that a certain amount of reactance is wanted in the transformer, but the author proposes later on that such reactance should be obtained separately outside the transformer, and it would look as though this would be the best arrangement. On page 206 the author alludes to the central position of the high-pressure tappings reducing to a minimum the unbalancing of the load in the low-pressure coils. It is not quite clear why equally favourable arrangements could not be made with this object, both on the core and on the shell type of transformer. On page 207 the author describes an arrangement for getting $1\frac{1}{2}$ turns on the

low-tension side instead of two turns. Fig. 5 is not clear on this point, and it would be of interest if he would explain exactly how the arrangement is carried out. Presumably there have to be a large number of half turns, since there are a large number of low-tension coils in parallel, and the question of the unbalancing of the flux in the magnetic fields has to be considered. With reference to the author's remarks on page 205 relative to the unequal lengths of the low-pressure coils which are in parallel, it is not clear whether the trouble is due to the reactance of the strips leading from the coils to the terminals, or to their resistance; I understood that these strips are interleaved so as to wipe out, as far as possible, the reactance. The core type of transformer would appear to be much more easily available for inspection than the shell type.

Dr. M. Kahn: The paper gives a very instructive comparison of the core-type and shell-type transformers when used for furnace work. There are advantages and disadvantages with either type of transformer which counterbalance one another more or less, although it appears that the shell type is easier to build and arrange than the core type. The author has in his statements mainly considered the question from the point of view of construction. A very important consideration in connection with the choice of the type from the user's point of view on this particular class of transformer is the question of repairs, as the apparatus is subject to particular heavy working conditions and breakdowns are more likely to occur and are of more serious consequence than in the case of the ordinary power or lighting transformer. If a coil on a shell-type transformer breaks down, the whole core has to be rebuilt, whilst on core-type transformers only the top yoke has to be removed. This advantage may decide the question, particularly on smaller sizes, where some of the considerations set out in the paper, for example the influence of the connections between coils and the bringing out of the leads, do not offer great difficulties on either type of transformer. On such transformers of small outputs it is possible to avoid connections between various sections of low-tension coils in parallel by arranging the low-tension winding in the form of a wide copper sheet which extends over the whole length of core and is wrapped round the iron in a spiral. It is essential with this construction to avoid uneven distribution of the flux by arranging the tappings in the middle of the core, otherwise considerable losses occur in the copper sheet. The connection from the low-tension winding to the furnace can be made by welding the connecting strips direct to the ends of the sheet before it is wrapped round the core. Transformers of this type up to 500 kw. have been used successfully on small furnaces. With a number of coils in parallel there is a certain danger of uneven current distribution, and it would be of interest to hear whether experiments have been made with thermo-couples in various parts of furnace transformers to detect cases of uneven loss distribution due to this or any other cause.

Mr. H. S. Holbrook: With reference to experiments with temperature indicators, I should like to ask the author if any tests have been made on transformers and boosters arranged in the manner shown in Fig. 6. It appears to me that the hot oil rising from the transformer would tend to overheat the booster windings. As regards the possibility of transformer windings containing $1\frac{1}{2}$ turns, the idea reads very well in the Patent Specification, and it would be interesting to know if it has proved as successful in practice. In presenting the figures on page 213 for the inductive drop in furnace lay-outs, the author has drawn attention to a very important matter which has not previously received sufficient attention.

Mr. F. Forrest: I think it is most essential that all large oil-cooled transformers should be provided by the manufacturer with an indicating thermometer or temperature detector, and such an instrument seems especially necessary in the case of transformers for furnace work which are subjected to severe short-circuits. These thermometers should be included whether they are called for or not by the purchaser, and it is the manufacturer's business to indicate to the buyer how essential it is that he should know the working temperature of the transformer windings.

Mr. W. Parry: I consider that the section on page 202 headed "Transformers for Steel Furnaces" should commence with a statement of the average values of current and voltage during a complete run, in order to see for which voltage the transformer losses should be a minimum. The author has given a well-balanced comparison between the shell and core type for furnace work. I should like him to extend the comparison to the case of a two-legged rectangular core-type transformer mounted horizontally in the tank. By using this type the low-tension leads could be made of practically the same length and without joints, as in the case of the shell type, and the ventilating ducts between the coils would be in the same direction as the natural flow of oil and could be insulated on the same method as the shell type. There would also be plenty of room to bring up the high-tension leads without congestion. There is the further advantage that the economic proportions of copper and iron can be reasonably obtained, also a butt joint in the core can easily be used to facilitate repairs. With regard to the high-tension terminals, I am of opinion that they should be brought through corrugated porcelain and that in exceptionally dirty conditions they should have at least one petticoat to obviate the possibility of a flash-over. On page 205 the author states that the low-tension leads are left bare. Would it not be advisable to tin the copper all over to reduce catalytic action tending to make the oil sludge? I should like to know if there is any evidence of direct current in the low-tension side due to a possibly rectifying action of the arc. With regard to the different power factors at different periods of the run, I should like a little more explanation. Between the melting period and the molten period there is a difference of 16·5 per cent in the reactance of the circuit. This difference must originate in the bath. Is it correct, therefore, to assume that it is due to the molten steel having lost its magnetic properties? Most transformer manufacturers will agree with the author's conclusions that the most reliable transformer is one without any tappings on the high-tension side. Comparing Figs. 7 and 8, Fig. 7 appears to be the simpler

and more reliable, and to involve the use of least switchgear. Probably the cost of switchgear in Fig. 8 could be reduced by using a suitably placed auxiliary winding on the main transformer to operate the booster transformer. It is quite possible that on small sizes of transformers ordinary standard 600-volt knife switches might then be used. Current control may be obtained on the low-tension by the use of variable chokers, which are made similar to transformers. A fine wire winding of equal ampere-turns to the main current winding is used and short-circuited or opened automatically by a standard contactor. The choker would be of a rating of about 20 per cent of the output of the main transformer and would be somewhat expensive but very reliable.

Mr. J. L. Thompson (*in reply*): With reference to Mr. Taylor's remarks, the author states in the paper that the tappings are inserted in the middle of the winding to prevent the piling up of voltage on the switchgear due to auto-transformer effect when operating on the minimum high-tension winding for the highest low-tension voltage. If Fig. D represents the high-

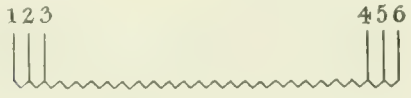


FIG. D.

tension winding of an 11,000-volt transformer with tappings for three low-tension voltages, viz. 65, 75, 85, then if the mains are connected to leads 1 and 6, 11,000 volts will come across these leads and 9,720 volts across 2 and 5, and 8,420 volts across 3 and 4. If the mains are across 2 and 5, then the pressure across 1 and 6 is 12,470 volts, and across 3 and 6 is 9,550 volts. If the mains are across 3 and 4, then the pressure across 1 and 6 is 14,400 volts, and across 2 and 5 is 12,700 volts. If the leads are all connected to selector switches, there is a possibility of 14,400 volts and 12,700 volts coming on these switches connected to 1 and 6 and 2 and 5 respectively. If the winding be as in Fig. E, then no

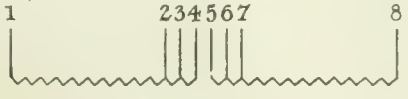


FIG. E.

pressure higher than 11,000, the line voltage, can come across any switch. In this case the voltage-increase is between switches connected to leads 2, 3, 4, 5, 6, and 7, and is only of relatively low value, the maximum being 3,400 volts. Three-phase furnace transformers are not insuperable but complex, and single-phase transformers are in the author's opinion most suitable for this type of work, giving more flexibility in location and also economy in spares. Over 90 per cent of the furnace equipments in this country are supplied with single-phase transformers. The suggestion that narrower and deeper coils would reduce the leakage path is quite correct, but this suggestion also reduces the reactance, and hence is not permissible for high-reactance transformers. The possibility of a central position for tappings on a core-type transformer is dependent on the reactance required, as Mr. Taylor suggests. An external reactance would not remove this difficulty, but would increase it, as with reduced reactance more groups of coils are required. A regulating transformer, however, would solve the problem. With regard to the use of $1\frac{1}{2}$ turns, this is fully described in the author's reply to the London discussion. The unbalancing of load in the parallel low-pressure coils is dependent on their resistance as well as on their reactance, and unless the parallel turns are equal in length, unbalance is bound to take place. Due to the comparative short length of copper in series in the low-tension winding, unequal length may cause a fair percentage of out of balance.

The repair of a core-type furnace transformer is not so easy as Dr. Kahn's suggestion implies. I would draw attention to Figs. 1 and 2 in the paper and would ask him if the transformer shown in Fig. 1 appears easier of repair than that of Fig. 2. The author would suggest that in either case the manufacturer would have to be called in to effect the repair. Dr. Kahn's suggestion of winding the low-pressure coils of furnace transformers of wide copper sheet may sound easy, but the author would suggest that failure will result if this practice is attempted on large sizes with high reactance. The leakage fields will cut this copper shield winding in parts at right angles and so cause heavy losses and local heating and eventually a burn-out or fusing of the low-pressure windings. Also, in this method of winding, the current will not be evenly distributed over the copper section, but will localize around the leads and the shortest path between the positive and negative leads. In a correctly designed transformer with all necessary ventilating ducts, no local heating is evident, and this is confirmed by experience and tests.

In reply to Mr. Holbrook, the suggestion of transformer and booster shown in Fig. 6 has not been built, but was inserted to show the possibility of such an arrangement. The booster would certainly be a little hotter than the transformer, but as it is surrounded by the cooling coil, the difference in temperature would be very small. With regard to the $1\frac{1}{2}$ turns, experiments were carried out on a large 2,200 k.v.a. transformer and the results proved the possibility of the scheme.

In reply to Mr. Forrest, thermometers and temperature alarms are fitted to many transformers, but only at special request. The suggestion that they be fitted as standard practice is good and the author agrees. If the transformer, however, is only loaded up to its rated capacity and given ample ventilation, the temperature should never rise to a dangerous figure.

With reference to Mr. Parry's remarks, in the author's opinion a core-type transformer mounted horizontally is not the most satisfactory design. This is because the transformer core being laminated in a horizontal direction cannot be rigid and is dependent on its rigidity by insulated bolts through the core, which are always under mechanical strain. The coils hang on the core and form a load on a laminated flexible beam, and hence cause vibration and sag. This is

more pronounced the longer the leg and the larger the size of the transformer.

The decrease in the inductive drop from melting to molten is not wholly due to the magnetic effect of the bath, but is also due to the fact that the load current is reduced and therefore the inductive drop. When the desired temperature is attained, the amount of energy required to retain that temperature is not so heavy.

North Midland Centre, at Sheffield, 23 March, 1920.

Mr. H. E. Yerbury: The troubles experienced at Sheffield with the transformers referred to, have, I believe, been largely due to the fact that they have been working almost entirely on two-phase furnaces. The suggestion has been made that certain transformer failures in Sheffield were due to resonance on the Electric Supply Department's mains, and I should like to ask the author what conclusions his firm reached after their investigations on resonance effects. What capacity of transformer does the author think should be the maximum as a single unit for furnace work, having regard to the heavy currents and connections, and overload ratings required, and other characteristics of very large sizes? The recommendations on page 211 of the paper are excellent, and will doubtless be followed by those responsible for laying out and installing furnace equipments.

Mr. F. S. G. Hinings: I am somewhat disappointed that the author has not dealt with other firms' manufactures. I myself am interested in the Berry furnace transformer, which is a circular shell type having a centre core upon which the windings are wound. We have supplied several hundred thousand kilowatts of this type during the war for furnace work alone, so I make no apology in pleading for this particular type of transformer. On turning to Fig. 1 in the paper, I notice that the interleaving of the low-tension bars is carried right through to the furnace, so that the actual contact can be on only one side of the busbars. I suggest that it is better to bring that interleaving just outside the top of the transformer tank and then separate the polarities and connect the busbars solid to them. In that way contact is obtained on both sides of the busbars. The connection shown in Fig. 1 appears to be rather long relatively to the width. If it is drawn to scale, it measures 2 ft. 8 in. × 8 in. and requires the use of a spring on each bolt for clamping. Is the bottom right-hand bolt, in the side view of Fig. 1, phosphor bronze or steel? That bolt seems to come within a magnetic field which may cause trouble. I am interested to hear of the author's patent, but on looking up our own records I find that the half-turn design was used by my Company in the early part of this century, although it was not patented. We have had half-turn transformers working quite satisfactorily during the last 15 years. On page 202 the author makes a great point of having the tappings in the middle of the winding. He seems to suggest that all the trouble would then be eliminated. I contend they are still liable to very high stresses and require also to be reinforced. I wish to endorse the statement that a lot of the early troubles of furnace transformers can be attributed to the insufficient capacity of such transformers. I know of several cases where the number of kilovolt-amperes mentioned to the transformer manufacturer had afterwards to be considerably increased; in fact small transformers were added to work in parallel with existing sets. This was not the fault of the transformer manufacturer, as he had not to determine the amount of power required for the furnaces. As far as the transformer is concerned I can see no limit to the size, but it is a question whether the supply authorities can deal with large loads of such an intermittent nature. I wonder how many supply authorities can deal with the 8,000 kw. furnaces mentioned by the author, especially if they are installed a long way from the generating station. In order to supply power to such large furnaces there is little doubt that it will be found necessary to distribute at higher voltages than in the past.

Mr. W. Redmayne: I can appreciate the transformer designer's difficulties from my own experiences with electric furnaces. The steel manufacturer finds that by taking $1\frac{1}{2}$ times full load he can melt steel much more quickly. He does it, and it is bad for the transformer. This overloading of the transformer breeds a contempt for the time-limit fuse, which frequently blows, and the result is that the normal fuse is replaced by a few turns of copper wire. The switch sometimes operates under these conditions, but this is due to good luck and a bad contact.

Mr. H. W. Walker: I have had experience of some of the breakdown difficulties in the Sheffield area with furnace transformers of various designs. Such failures are chiefly due to the unfair treatment that many transformers receive owing to inefficient handling. At a lecture the other evening a furnace designer stated that an electric steel furnace could be easily handled by men who had had only three weeks' training. I know that is done, and I imagine that quite half of the breakdowns are caused by such handling and inefficient electrical loading of furnaces. There is no doubt that the average furnace transformer is at least 50 per cent under-rated as regards the furnace capacity. This applies to most of the types installed. The author's remarks with reference to reactance regulators seem to me very necessary, but so far I have not come across a case where such a regulator has been installed. It is probably a question of cost. The author does not mention switchgear, which I think is a very important item of a furnace installation. I often find the time-limit fuse holder is discarded, and I have come across cases where a piece of 22 S.W.G. copper wire was wrapped round the contact clip. As to the maintenance of furnace plant, it will generally be found that the plant is sadly neglected which suffers a breakdown sooner or later. I believe that the supply authority at Sheffield has recommended that each switch should be opened out at least every month. This would be sufficient in ordinary cases, but I think that at least once a fort-

night the oil tank should be lowered to note if the oil needs changing. In a month the oil becomes badly carbonized; at least it did so when the war was on and the transformers were pushed hard. Can the author give us any idea as to how often a transformer winding should be lifted and the oil examined? I consider that permanent recording meters should be installed under lock and key, to give some indication of what is done on night shift.

Mr. J. L. Thompson (*in reply*): I regret that I am unable to reply to Mr. Yerbury's queries, but if he will refer to my reply to the London discussion (page 220) he will note that Scott-connected transformers for two-phase furnace work are liable to be seriously overloaded under adverse conditions. Transformers for three-phase furnaces are relatively simple in design, and overloading during normal operation is not possible without being immediately noted on the measuring instruments. With reference to resonance, I must also be excused from a direct reply. If a supply system is laid out on the star feeder system, it has been demonstrated that the dead end of any feeder is the most vulnerable point for surge voltages. This is because the high-frequency surges are reflected at the dead end and the synchronizing of the direct and reflected waves will cause a high-voltage surge. A ring-main system would seem to be the one most suitable when heavy surges of current are a frequent possibility. I have pointed out in my replies at the other Territorial Centres that there is no limit to the size for which a furnace transformer can be built, but that the furnace for steel work tends to approach a limiting size of 8,000 k.v.a. This size is dependent on present knowledge and future investigation, and research may show the possibility of raising this limit to a much higher figure.

I would draw Mr. Hinings's attention to the fact that no particular firm's manufactures are dealt with in the paper. The two types mentioned are those universally known, while that mentioned by Mr. Hinings is peculiar to one firm's manufacture. The interleaving of the low-pressure bars is essential where the current to be carried is heavy, and especially where the run of the low-pressure leads is of any length. The question of contact surface is relatively unimportant as long as sufficient surface is obtained. By the use of two bars and two contact surfaces, increased losses are experienced at these contacts due to alternating current cutting two surfaces at right angles, as against one surface only. The introduction of separate groups of positive and negative leads will cause trouble on large transformer equipments above 500 k.v.a., as mentioned in the paper. The use of springs in connection with low-pressure lead clamps permits of ease in erection and also tends to keep the surface contact of the bars constant at all temperatures. The bolt mentioned by Mr. Hinings in Fig. 1 is of steel, but the clamping plates are of non-magnetic material. The bolt will not get hot, since the bars are interleaved and the leakage fields are therefore neutralized in the region of the bolt. With reference to Mr. Hinings's remarks re my patent, I would suggest that although half-turn windings may have been used many years ago, it was done in an unscientific way. For instance, they have been used, as I am aware, for starting tappings in connection with rotary-converter transformers, but in those cases they could not be run continuously without very high temperature rises in the iron circuit. This excess loss is due to the unbalancing of the load fluxes in the core, with a result that the iron was over-saturated. Further, the reactance of such a transformer when loaded on the half turn is very high, due to the unbalanced flux, and the characteristic of the reactance voltage with load is similar to a B/H curve. A transformer designed to my patent is, however, quite normal under all conditions of load, and the reactance characteristic is a straight line and the flux throughout the core and under all load conditions is balanced. If Mr. Hinings studies the patent specification and compares it with the designs he mentions, he will find the differences referred to. The suggested central position of the high-pressure tapping was not made to eliminate high-pressure surges, but to prevent high induced pressures from coming on the switchgear and terminals (see my reply to the Birmingham discussion, page 305). The low rating of transformers for furnace work has already been mentioned, and I am in agreement.

Mr. Redmayne agrees regarding the difficulties that transformer designers have experienced, and his statements are further evidence and support the suggestions outlined in the paper with reference to control and supervision.

Mr. Walker's statements also support the author's remarks re control and supervision. If operation and supervision were given more attention, much trouble would be eliminated and expense saved. I would advise that a transformer under continuous load and frequent overloads should be examined every six months, and that samples of oil should be taken from the tanks and examined casually every three months. If any discoloration, sludge or moisture be noted, it should be carefully examined and tested, and, if found defective, filtered or renewed as the case may be. The condition of the oil will indicate the condition of the transformer. If excessive sludging is noted, it would be advisable to lift the transformer and clean it before renewing or filtering the oil. The suggestion that recording meters should be used on furnace installations meets with my approval, as it will be an additional safeguard and a visible means of ascertaining when excessive loads are taken and by whom. They would also be of assistance to insurance companies in their periodic inspection, and especially in cases of failure.

REPORT OF THE COUNCIL FOR PRESENTATION AT THE ANNUAL GENERAL MEETING OF 20 MAY, 1920.

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REPORT.

The Council at the Forty-eighth Annual General Meeting of The Institution of Electrical Engineers, present to the members their Report for the year 1919–20.

(1) Membership of the Institution.

The changes in the membership since the 1st April, 1919, are shown in the following table :—

	Hon. Mem.	Mem.	Assoc. Mem.	Grad.	Studt.	Assoc.		Total.
Totals at 1 April, 1919 (Estimated)	8	1,524	3,833	519	680	459		7,023
Additions during the year :—								
Elected	1	25	498	185	553	29		
Reinstated	..	..	2	..	39	18		
Transferred to	..	77	84	47	..	..		
Total	1	102	584	232	592	47	1,558	
Deductions during the year :—								
Deceased	..	14	30	4	7	6		
Resigned	..	9	37	13	26	9		
Lapsed (Estimated)	..	16	105	66	12	2		
Transferred from	..	..	73	48	75	12		
Total	..	39	245	131	120	29	564	
Net Increase	..	..	..	..	..	..	..	994
Totals at 1 April, 1920 (Estimated)	9	1,587	4,172	620	1,152	447		8,017

The growth of membership is emphasized by comparison with the corresponding totals for the last few years, which are as follows :—

Year	Membership		Increase or decrease
1912	6,537	+	194
1913	7,084	+	547
1914	7,045	—	39
1915	6,811	—	234
1916	6,676	—	135
1917	6,613	—	63
1918	6,667	+	54
1919	7,023	+	356
1920	8,017	+	994

The Council are gratified at the large increase of membership, which, though no doubt due in part to new members now joining the Institution who were prevented

from doing so while the War continued, is to be chiefly attributed to the increased usefulness of the Institution and to the activity of the Territorial Centres and Sub-Centres.

(2) Honorary Member.

The Council have pleasure in recording the announcement made at the Ordinary Meeting of the 13th November last that they had elected Professor Hendrik Antoon Lorentz, of Leyden University, Holland, to be an Honorary Member of the Institution.

(3) Honours and Distinctions Conferred on Members.

Military distinctions arising out of the War have been awarded during the year as follows:—

Distinction	No. of Awards
K.B.E.	1
C.M.G.	4
C.I.E.	2
C.B.E.	6
O.B.E.	38
D.S.O.	2
M.B.E.	21
A.F.C.	1
M.C.	16
M.S.M.	2
T.D.	7
Legion of Honour, Croix d'officier	1
Legion of Honour, Chevalier	2
Croix de Guerre (French)	2
,, ,, (Belgian)	2
,, ,, (Portuguese)	2
Ordre de Leopold, Officier	1
Ordre de la Couronne, Chevalier	2
Military Order of Aviz	2
Ordre de l'Etoile Noire	1
Order of the Crown of Italy, Officer	1
Mentioned in despatches	53
Mentioned	2

Lists of names of the recipients have been published in the *Journal* (Vol. 57, *Institution Notes*, No. 14, p. 30; and No. 15, p. 40).

The following honours have also been conferred on members:—

K.C.B.

Glazebrook, Sir R. T., C.B., D.Sc., F.R.S. (Member).

K.B.E.

Devonshire, James (Member).
Elphinstone, G. K. B. (Member).
Mansfield, A., C.B.E. (Associate).
Petavel, J. E., D.Sc., F.R.S. (Associate Member).
Renwick, H. B. (Associate).
Ruck, Major-General R. M., C.B., C.M.G. (Member).

Knighthood.

Kemnal, J. H. R. (Member).
Schuster, Prof. A., F.R.S. (Member).

C.B.E.

Anderson, J. (Associate).
Clough, F. H. (Member).
Dalrymple, J. (Associate).
Fell, A. L. C. (Member).
Fleming, A. P. M., M.Sc., O.B.E. (Member).
Hunter, P. V. (Member).
Larke, W. J., O.B.E. (Member).
Le Maistre, C. D. (Member).
MacGregor, J. J. (Member).
Preston, G. F. (Member).
Pybus, P. J. (Member).
Scholey, H. (Member).
Sparks, C. P. (Member).

O.B.E.

Allen, P. R. (Associate).
Barclay, W. R. (Associate Member).
Bisacre, F. F. P. (Associate Member).
Boulding, R. S. H. (Associate Member).
Brousson, R. P. (Member).
Crompton, Capt. C. (Associate Member).
Dannatt, F. C. (Associate Member).
Drysdale, Dr. C. V. (Member).
Faber, O., D.Sc. (Associate Member).
Gill, F. (Member).
Goodyer, T. B. (Associate).
Hawes, G. W. S. (Member).
Moat, W. (Associate Member).
Orr, Prof. J. (Associate Member).
Parker, E. T. (Associate Member).
Pollock, S. A. (Member).
Pringle, J. S. (Member).
Rodgers, C. (Associate Member).
Rogers, H. I. (Member).
Sandberg, O. F. A. (Associate).
Sayers, J. (Member).
Scott, W. H. (Member).
Sinnott, J. (Member).
Spencer, C. J. (Member).
Thornton, Dr. W. M. (Member).
Tough, G. (Member).
Watson, E. A. (Associate Member).
Williams, E. T. (Member).
Young, A. P. (Member).

M.B.E.

Brakes, H. (Associate Member).
Coutts, F. (Associate).
Fisher, F. (Associate Member).
Frankling, A. E. (Associate Member).
Haler, P. J. (Associate).
Hardy, W. E. (Member).
Hatch, W. A. (Associate Member).
Heron, C. R. (Associate Member).
Huddart, A. H. (Associate Member).
Hudson, Russell (Associate Member).
Hunt, F. C. (Associate Member).
Jervoise, E. (Associate Member).
Jones, H. J. A. (Associate Member).
Kilgour, M. H. (Member).
Malcolm, G. W. (Member).

M.B.E. - *continued.*

Ramsey, A. G. (Associate Member).
Roberts, A. H. (Associate Member).
Robson, W. T. (Associate Member).
Rycroft, P. E. (Associate Member).
Watlington, V. (Member).
Webb, G. R. (Member).
Wilmshurst, T. P. (Member).
Worrall, G. W., D.Eng. (Associate Member).

Ordre de la Couronne, Chevalier (Belgium).

Joly, H. L. (Associate Member).

(4) Deaths.

The Council have to deplore the death of 55 members of the Institution during the year, of whom 9 lost their lives on naval or military service.

Roll of Honour.

Killed in Action.

Clarke, Private R. St. J.	N.Z. Trench Mortar Battery	Student
Reynolds, Gunner O. B.	N.Z. Artillery	Student

Accidentally Killed.

Wright, Lieut. C. V. C.	Royal Air Force	Associate Member

Died.

Barter, Leading Seaman A. E.	Royal Naval Division	Student
Bly, 2nd Lieut. H. A. E.	Royal Garrison Artillery	Student
Hayne, Capt. E. T., D.S.C., D.F.C.	Royal Air Force	Student
Murphy, Lieut. G. H.	Royal Naval Air Service	Graduate
Prince, Lieut. G. R. D.	Royal Engineers	Associate Member
Twigg, Private J. H.	Royal Army Service Corps	Associate Member

A Service in memory of the members of the Engineering Profession who lost their lives in the War was held at Westminster Abbey on Wednesday, 18th June, 1919, and was attended by a large number of members of this and other Engineering Institutions.

Other Members Deceased.

Members.

Banneux, J.
Barlow, H. D.
Bihet, O.
Bumiller, R. B.
Carhart, Prof. H. S.
Connolly, J.
Dorman, C. M.
Drugman, L.
Lineham, W. J.
McDonald, Rt. Hon. Sir J. H. A., G.C.B., LL.D., F.R.S.S.
Ruddle, M.
Starr, D. A.

Associate Members.

Berry, J. R.
Bingham, H.
Blair, G. C.
Cohen, S.
Foale, W. S.
Forsdick, C. F.
Fyfe, J. J.
Garnett, C.
Harford, G. J.
Harris, A. R.
Haslam, L. F.
Jack, J. W.
Johnson, L. W.
Mittra, K. C.
Moulden, E. S.
Pyne, Major F. D., O.B.E.
Reichel, L. T.
Roseveare, L.
Stockbridge, J. P.
Thorpe, H.
Waller, A.
Weston, P. L.
Wilson, G. H.

Associates.

Ardron, J., C.B.
Benedict, W. C.
Gemmel, T.
Malden, G. F.
Vinçotte, R.
Walter, A. J., K.C.

Graduates.

Conner, W. G.
Kemp, H. D.

Students.

Boyton, E. F.
Haywood, J.
Orpin, C.

Among the deaths recorded above, the Council feel particularly the loss of the following colleagues: Mr. J. Ardron, C.B. (Member of Council in 1895), M. J. Banneux (Local Hon. Secretary and Treasurer of the Institution for Belgium from 1907 to 1912), Mr. M. Ruddle (Chairman of the Dublin Local Section, now Irish Centre, during 1904–5), Mr. D. A. Starr (Chairman of the Scottish Local Section, now Scottish Centre, during 1915–16), and Mr. A. J. Walter, K.C. (Member of Council from 1903 to 1906).

(5) War Memorial.

The Council are glad to report that, as far as they have been able to ascertain, the number of dependents of fallen members whose circumstances would warrant assistance from the War Memorial Fund is negligible, with the result that a larger proportion of the amount subscribed will be available for a suitable Memorial in the Institution Building. The Council are anxious that no case needing assistance shall escape their notice and members knowing of such cases are therefore requested to communicate with the Secretary of the Institution. But the question of the Memorial itself must necessarily stand over until the Institution is reinstated in its quarters.

The book of biographies and portraits of members who lost their lives in the war is in active preparation, and with the object of making the record as complete as possible, the Council are endeavouring to obtain further biographical details.

(6) Electrical Appointments Board.

As has already been reported, the Electrical Appointments Board which, in order to comply with legal requirements, is an organization separate from the

Institution, has been set up with the object of acting as intermediary between employers and members seeking employment.

Owing to the limited number of vacancies reported, the Board have decided that, for the present, members who have served in H.M. Forces shall receive primary consideration.

(7) Benevolent Fund.

The Committee of Management of the Benevolent Fund of the Institution report that on the 31st December, 1919, the Capital Account of the Fund stood at £5,709 9s. 6d., and the accumulated income at £1,750 5s. 8d. The donations and subscriptions to the Fund in 1919 amounted to £537 7s. 8d.

In the course of the year 24 grants were made, amounting to a total of £291 5s.

The following is a comparison of the number of subscriptions and the amounts received up to the 15th April during the present year and for the same period a year ago :—

	Number of Subscribers	Amount Subscribed £ s. d.
1920		
1 January to 15 April		
From members	712	£418 6 10
.. City of Glasgow Royal Engineer Volunteers (per Major E. T. Goslin)	1	197 0 11
.. County of London Royal Engineer Volunteers (per Sir John Snell)	1	31 9 6
.. Midland Electrical Engineers Ball Committee	1	30 0 0
	715	£676 17 3
1919.		
1 January to 15 April	570	£422 0 6

The Accounts of the Fund, which are separate from those of the Institution, will be published in a later number of the *Journal*.

(8) Benefaction to the Institution.

On behalf of the Institution the Council have accepted with grateful thanks the benefaction referred to in the following letter :—

Gwydyr House,
London.
19th April, 1920.

Roger T. Smith, Esq.,
President,
The Institution of Electrical Engineers,
1, Albemarle Street, W. 1.

Sir,

We have been requested by a donor, who desires to be anonymous during his lifetime, to transfer to Trustees for The Institution of Electrical Engineers as a thank-offering to God for mercies vouchsafed to him during the War, a sum of £2,000 5% War Loan and in the following terms, viz. :—

The interest on this Stock to be applied in such a way as the Council of The Institution of Electrical Engineers in its uncontrolled discretion may think fit

(*a*) in the first place, to assist the education of one or more of those of our countrymen, not being a conscript, who has or have served Overseas during the Great War, and who is or are anxious to enter the Profession of an Electrical Engineer, and

(*b*) in the second place and subject thereto, to promote general Electrical Research.

Will you kindly inform us of the names of the Trustees to whom the Council desires us to transfer the Stock ?

We are, Sir,
Your obedient Servants,
(Signed) John Snell.
(Signed) Sydney Morse.

(9) Associate Membership Examination.

In view of the return to normal conditions, the Council have rescinded the suspension of the Associate Membership Examination Rules, and in future, except as provided below, candidates for Associate Membership who do not possess one of the exempting certificates or diplomas or have not submitted a satisfactory thesis will be required to pass the Examination. In the case of applicants who have attained the age of 35, the Council may in their discretion dispense with the examination and the thesis.

(10) The Institution Building.

The Council very much regret to state that their efforts for the reinstatement of the Institution in its Building have so far proved unsuccessful. Arrangements are being made for a deputation of the Council to wait on H.M. Commissioner of Works to urge the necessity for early reinstatement.

(11) Members' Subscriptions.

The return of the Institution to its own premises will compel special reconsideration of financial provision for the future. Practically all expenses of administration and the cost of everything that the Institution has to buy have shown a considerable advance since the Institution was in its own home ; and when it returns to adequate accommodation and full activities, it is more than probable that the revenue will fall short of the actual requirements, notwithstanding the exercise of the strictest economy. If the activities of the Institution are to be maintained and extended some increase in the subscriptions may have to be proposed.

(12) Library.

Owing to the continued retention of the Institution Building by H.M. Office of Works, the bulk of the Institution Reference Library, the entire Ronalds' Library, and the collection of historic apparatus in the possession of the Institution are still inaccessible to members.

By kind courtesy of the Council of the Institution of Civil Engineers, the Library and Reading Rooms of that Institution continue to be at the disposal of members. The Library and Reading Rooms are open on weekdays from 9.30 a.m. to 5.30 p.m., excepting on Saturdays, when they are closed at 1 p.m.

During the past year 167 books and pamphlets have been presented to the Reference Library by members and others.

The Council wish to remind members that the Lending Library is available for those who wish to borrow books. During the year 667 books were issued to 300 borrowers, the corresponding numbers in the previous year being 497 and 205 respectively. The catalogue is under revision, and copies will be obtainable on application at an early date.

(13) Museum.

A number of valuable acquisitions to the Museum have been made during the past year, notably from the laboratory of the late Sir William Crookes, O.M., a Past-President of the Institution. The list of additions is as follows :—

Apparatus from the Laboratory of the late Sir William Crookes, O.M.	*How Acquired.*
21 early forms of radiometers and spectrum tubes.	Presented by Bernard Crookes.
A collection of tubes containing meteoric gases.	do.
10 early types of glow lamps.	do.
An early pattern telephone receiver.	do.
A McLeod gauge.	do.
A vacuum pump.	Presented by G. L. Addenbrooke.
A large induction coil.	Purchased.
A spectrograph, including maps, volumes and original negatives.	do.
A collection of vacuum tubes (1891).	do.
A Moissan furnace.	do.
An early form of electric arc lamp.	do.
A chemical balance.	do.
Other Apparatus, etc.	
A collection of German wireless apparatus.	Presented by the War Office.
An early Edison dynamo.	Presented by R. W Paul.
A collection of papers, letters, MSS., etc., of electrical interest from about 1865 to 1918, and a number of engravings and photographs of old telegraph apparatus.	Presented by J. J. Fahie.
A Kelvin electrical balance.	Presented by C. E. Hunter.

The Council desire to acquire apparatus of interest in connection with the War, and members possessing or able to obtain such apparatus are invited to communicate with the Secretary.

(14) Ordinary Meetings.

The Ordinary Meetings held in London for the reading and discussion of papers have been well attended.

(15) Territorial Centres and Sub-Centres.

The representation of Territorial Centres on the Council by their Chairmen and Past Chairmen keeps the various Territorial Committees in close touch with the work of the Council, and on the other hand the activities of the Territorial Committees in association with local bodies concerned with education, scientific libraries, training of disabled men, employment of demobilized men, and commerce, provide for a representation of the views of the Institution which would otherwise be difficult to secure. The work of the Territorial Centre Committees is regarded by the Council as of the utmost value to the Institution.

During the session Sub-Centres of the Territorial Centres have been formed at Aberdeen, Dundee, Liverpool, Preston, Loughborough and Sheffield. The Council hope that the formation of these Sub-Centres will further increase the interest in the affairs of the Institution of those members who have found it difficult hitherto to attend meetings of the Territorial Centres.

The Council have drawn up Rules for conducting the business of the Sub-Centres.

The Meetings at the various Territorial Centres and Sub-centres have been well attended and have included social reunions, dinners and informal meetings.

During the Session the President, Mr. Roger T. Smith, visited each of the Territorial Centres in Great Britain and also the Sub-Centres at Liverpool and Sheffield, where his presence was much appreciated.

(16) Wireless Section.

The Wireless Section of the Institution which was formed in the Spring of 1919 has since its formation held 8 meetings, at which papers dealing for the most part with the development of Wireless Telegraphy and Telephony during the War have been read and discussed. The average attendance at these meetings was over 140.

The Council have drawn up rules for conducting the business of the Section, and they will be brought into operation at the beginning of next session.

(17) Informal Meetings.

The Council have received from the Informal Meetings Committee a highly satisfactory report, of which the following is an abstract.

Eight Informal Meetings have been held during the current session, the matters under discussion being the following :—

Subject of discussion.	*Introduced by*
" Engineering Advertising."	W. E. Warrilow.
" Some Reflections on Labour."	R. Rankin.
" Functions of a Trade Journal."	F. H. Masters.
" Engineering Experiences during the War."	Major T. Rich.
" Automatic Telephony for Private Branch Exchanges."	A. B. Eason.
" The Future of Labour in the Engineering Industry."	R. E. Dickinson.
" Industrial Electric Heating."	J. W. Beauchamp and S. M. Hills.
' Group versus Individual Drive by Electric Motors."	G. H. Ayres.

The attendances have ranged up to 80 and the discussions have been well sustained and full of interest.

A highly successful Smoking Concert was given at the Albert Tavern on March 29th, 1920, at which 120 members were present.

Eight Committee Meetings have been held. The Committee now consists of Messrs. R. Rankin (Chairman), W. E. Bradshaw, R. D. Gifford, A. F. Harmer, S. M. Hills, G. C. Law, F. Pooley, W. E. Warrilow, and W. L. Wreford.

The meetings which were originally arranged to be held at monthly intervals have proved so popular that they are now held fortnightly, the subjects for discussion being readily forthcoming, and the attendance well sustained.

The Council hope that the interest shown will be continued, and that the senior members of the Institution will as hitherto help by their attendance at the meetings and by taking part in the discussions.

(18) Students.

Since the Armistice the Students' Sections have shown considerable increased activity, and the Council are also pleased to record the formation of a new Students' Section in connection with the Liverpool Sub-Centre. The total number of Students' Meetings was 27, and in addition a number of interesting visits to works were paid during the session.

Addresses to the Students' Section in London were given by the President (Mr. Roger T. Smith), and Mr. A. P. Trotter.

The great expansion of the work of electrical engineers which is taking place in all parts of the world makes it in the opinion of the Council of particular importance at the present time for the Institution to have regard to the interests of the younger members.

It may therefore be of interest to record the special facilities which exist for them, in addition to the benefits of membership which they share with other classes.

Students' Meetings and Lectures are held in London and at certain Territorial Centres. Premiums are awarded for Students' papers, and in addition to the Institution premiums the Council have pleasure in acknowledging the generous action of the B.E.A.M.A. in making special awards for contributions to their *Journal* from Institution Students.

The advantages of the lending library are open to Students, and the Council note with approval the increased use which is being made of it.

(19) Meetings.

A statement of the total number of meetings and conferences held during the past twelve months will be found in Appendix A to this Report.

(20) Conversazione.

A Conversazione and Reception to meet members of the Institution who had served in H.M. Forces during the War was held at the Natural History Museum, Cromwell Road, S.W., on Wednesday, the 25th June, 1919. On this occasion a short Address of Welcome to the large number of service members present was given by the then President, Mr. C. H. Wordingham, C.B.E.

(21) Annual Dinner.

Since the last Report the Annual Dinners of the Institution for 1919 and 1920 have taken place at the Connaught Rooms, Great Queen Street, London, W.C., on the 26th June, 1919, and 4th March, 1920, respectively. Both functions were attended by large numbers of members and distinguished guests.

(22) Deputation to Holland.

By invitation of the Dutch Association of Electricity Works' Managers, a small deputation of members of the Institution, representative of the various branches of the industry, visited Holland in September, 1919. The visit was of great interest to the deputation, and a detailed Report appeared in last year's *Journal* (No. 285, *Institution Notes*, p. 34).

Arrangements are being made for a return visit of Dutch Engineers to this country in July next. It is hoped that the visitors will also take part in the Summer Meeting of the Institution at its Western Centre.

(23) Papers.

A list of the papers read during the session 1919–20, and also of those published without being read at meetings, will be found in Appendix B to this Report.

(24) Kelvin Lecture.

The Eleventh Kelvin Lecture was delivered by Dr. C. V. Drysdale, Member, on the 15th April, 1920, the subject of the lecture, at which there was a good representative attendance, being "Modern Marine Problems." The lecturer dealt with some of the new discoveries made during the War in the detection of ships, submarines and icebergs, and determining the position of ships and land and sea stations under conditions of invisibility.

(25) Premiums.

The premiums awarded by the Council for papers will be announced at the Annual General Meeting.

(26) Scholarships.

The following Scholarships have been awarded by the Council :—

David Hughes Scholarships.

(Value £50 ; tenable for one year.)

D. S. Anderson (Royal Technical College, Glasgow).
B. A. Cronin (University College, Cardiff).
P. D. Morgan (King's College, London).

Salomons Scholarships.

(Value £50 ; tenable for one year.)

H. J. Barriscale (University College, Cork).
R. Cribbes (Heriot Watt College, Edinburgh).
J. C. Reid (Bristol University).

Paul Scholarship.

(Value £25; tenable for one year.)

F. E. Price (Finsbury Technical College).

This is the first occasion on which effect has been given to the Council's decision to extend the scope of the David Hughes and Salomons Scholarships by opening them to Students in the provinces.

(27) Local Centre in Argentina.

The Council are glad to report that a further Local Centre of the Institution abroad has been established for Argentina, with headquarters at Buenos Aires.

(28) The Council's Work.

The Session has been an active one and, in addition to the continuance of the ordinary work of the Institution, the Council have given consideration to special matters affecting the interests of members and of the industries in which they are engaged; and they have taken action, either independently or in co-operation with other bodies, in promoting new developments which they considered likely to be beneficial to electrical engineers and in the safeguarding of the interests of members.

The Council have been encouraged in their work by the large increase of membership which has taken place since the termination of the War and by the increased appreciation of the work of the Institution which is thus apparent.

The work of the Council and of its Committees has involved a considerable call on the time of the members of Council, many of whom are provincial members and have to travel far to attend.

(29) National Electrical Proving House.

The Committee, consisting of representatives of various interested bodies and appointed by the Council, has reported on the question of an Electrical Proving House. The Committee's Report has been considered by the Board of Trade, and in the summary of the Government's proposals published in August 1919 the matter was referred to as follows:—

"It is proposed to set up at the Board of Trade a Department of Standards, (1) to promote and co-ordinate standardization generally, and (2) to establish and administer such testing institutions as may be found necessary, and authorise and, so far as may be required, supervise the testing work carried out by technical institutions, trade organizations or private concerns.

(30) Electricity Supply Bill.

In July 1919 the Council addressed a memorandum to the Prime Minister, the full text of which will be found in the *Journal* (vol. 57, *Institution Notes*, No. 15, p. 38).

Under the terms of the Electricity Supply Act, which passed into law on the 23rd December, 1919, five Commissioners have been appointed, of whom, the Council are pleased to put on record, three are Members of the Institution.

The Commissioners appointed are the following:—

Sir John Snell, Member (Chairman).
Mr. H. Booth, O.B.E.
Sir H. E. Haward.
Mr. W. W. Lackie, C.B.E., Member.
Mr. A. Page, Member.

In accordance with the King's speech at the opening of the present session of Parliament, a further Bill has been introduced in the House of Commons, and is now under consideration. It is receiving the close attention of the Council.

(31) Patent Law Amendment.

The efforts of the Institution Patents Committee to obtain certain improvements in the Patent Law, referred to in last year's Annual Report, were continued in association with other Institutions in connection with the passing through Parliament of the new law (Patents and Designs Act 1919), with the effect that certain modifications were made, but on the whole the result was disappointing.

(32) Coal Prices and Supplies.

During the session several Deputations representative of Electricity Supply, and organized by the Institution, were received by the Controller of Coal Mines in regard to coal prices and supplies and giving to the consumer the benefit of the rebate on coal used for domestic purposes.

The Council regret that from the point of view of Electricity Supply Stations the question of coal prices and supplies is still on a very unsatisfactory basis, and they have arranged for further conferences to consider the matter and make further representations to the Government Departments interested.

(33) Overhead Power Lines.

The Committee appointed by the Council last Session to consider and report on Regulations for Overhead Power Lines (excluding tramway working conductors) will shortly present its first Report to the Council.

(34) Registration of Civil Engineers.

The Civil Engineers' Registration Bill, promoted by the Institution of Civil Engineers, received the most careful attention of the Council and of a Special Committee during the period under review. In the event of the Institution of Civil Engineers having proceeded with their original proposal the Council had made arrangements to ascertain without delay the views of the members as a whole and to act accordingly. The original proposal was, however, amended, and subsequently the Council discussed the matter with the Institution of Civil Engineers. Since then, the latter body have intimated that it is not their intention to proceed further with a Bill in the present session of Parliament. Negotiations in such a matter are necessarily confidential, and the Council cannot publish details, but desire members to know that their interests,

together with those of the whole engineering profession with which they are bound up, have their first consideration.

(35) Institution "Journal."

The amount of matter received for the *Journal* continues to increase, and the papers and communications published cover a wide range of subjects. The heavy cost of publication has, however, had the effect of preventing the publication of valuable matters which would otherwise have appeared in the *Journal*.

With the object of making the *Journal* of the greatest value to the members a Committee of the Council have under consideration the question of its future form, and whether with a view to economy it should be divided into sections of interest to various groups and circulated accordingly.

The Council will welcome suggestions from members in regard to improving the *Journal*.

(36) "Science Abstracts."

The Physics volume of "Science Abstracts" for 1919 showed an increase in size over that for 1918, while the Electrical Engineering volume was of the same size as in 1918.

Owing to the continued increase in the cost of the publication, the Council regret they have been compelled to increase the subscription rates.

(37) Wiring Rules.

The Council have decided to undertake a complete revision of the Wiring Rules. The Committee, which is now under the Chairmanship of Mr. C. H. Wordingham, has, in order to deal with the work as thoroughly and expeditiously as possible, set up the following Sub-Committees under the respective Chairmen named :

Sub-Committee.	*Chairman.*
(1) Cables, Wires and Flexibles	Mr. W. Cross.
(2) Earthing	Mr. W. R. Rawlings.
(3) Fittings	Mr. J. R. Dick.
(4) Motors, Arc Lamps, Resistances, Heating Apparatus, etc.	Mr. J. R. Cowie.
(5) Planning of Installations ..	Mr. S. G. C. Russell.
(6) Editing	Mr. C. H. Wordingham.

Pending the complete revision, a table of current-carrying capacities of cables was issued in October 1919 in connection with the British Engineering Standards Association's new list of standard sizes of copper conductors. The minimum permissible size of conductor has also been revised.

The Committee has been strengthened by an additional representative of the Electrical Contractors' Association and by a representative of the Association of Supervising Electricians.

(38) Regulations for the Electrical Equipment of Ships.

The Regulations for the Electrical Equipment of Ships were published in September 1919, and have been very favourably received.

Lloyd's Register of Shipping have decided to issue a new set of electrical regulations for work done under their survey, and have embodied in them the Institution's Regulations. The Council note this action with much gratification, since it will tend to the establishment of a satisfactory standard of work on mercantile ships, at the same time showing that the work of the Committee has already proved of service to the shipping industry.

Any suggestions and the published criticisms of the Rules will be considered by the Standing Sub-Committee in order that a revision may take place when found necessary.

During the year one meeting has been held of the Standing Sub-Committee, when an important discussion took place on the status of sea-going electricians, with the result that the Council have communicated the following Resolution to the Board of Trade :

"That in view of the growth in the use of electrical power on ships, it would be desirable that the Board of Trade should consider the advisability of holding examinations and granting certificates to duly qualified electricians on sea-going ships."

The Council have also expressed their willingness to prepare an examination scheme, if required.

(39) Maintenance Agreement for Secondary Batteries.

The Council regret that owing to conditions beyond their control very little progress has been made with the preparation of a Standard Maintenance Agreement for Batteries.

(40) The Institution and Bodies on which it is Represented.

For the convenience of members, there is attached hereto (Appendix C) a diagram showing the organization of the Institution and its relation to other bodies.

(41) Institution of Engineers (India).

The Council have given their cordial support to the formation of the Institution of Engineers (India). One of the main objects of the new Institution is to raise the status of all branches of the engineering profession in India, and as a mark of their interest the Council have offered for five years on behalf of the Institution of Electrical Engineers an annual premium of the value of £20 for the best paper on an electrical subject read before the new body.

(42) International Electrotechnical Commission.

During the past year the International Electrotechnical Commission have recommenced their activities, and in addition to the Plenary Meeting held in London in October last, a meeting of a number of its Advisory Committees was held recently in Brussels under the Chairmanship of the President of the Commission, Dr. C. O. Mailloux, and M. Omer de Bast, Chairman of the Belgian National Electrotechnical Committee.

The British Electrical Industry was represented by Mr. C. H. Wordingham, C.B.E., Major K. Edgcumbe, R.E.(T), Mr. A. R. Everest, Mr. C. Rodgers, Mr. A. J. Stubbs, Mr. C. C. Wharton, and Mr. W. B. Woodhouse.

Rapid progress is being made in regard to International Rating of Electrical Machinery, and Part I of the I.E.C. Rating Rules dealing with small machines is now available ; Part II, dealing with large machines, is now under discussion, and at the Brussels Meeting proposals of the American Committee regarding the question of Embedded Temperature Detectors were very fully discussed.

The question of Nomenclature and of Graphical Symbols is being dealt with as rapidly as possible.

(43) British Engineering Standards Association.

During the past year a large expansion has taken place in the work of the Electrical Section. Considerable progress has been made with many matters of great importance to the Electrical Industry.

The closest possible co-operation with the Electrical Research Committee is assured, and some of the B.E.S.A. Panels have taken steps in conjunction with that Committee to inaugurate the necessary research work, particularly in regard to control gear.

(44) Electrical Research Committee.

The organization of the Electrical Research Committee referred to in the last Annual Report has been proceeded with and is now nearly complete.

The organization provides for (*a*) Sectional Committees acting in an advisory capacity and representative of the interests in (i) a given section of the industry, or (ii) a given group of materials, and (*b*) Sub-Committees of experts with executive powers acting under the Sectional Committees.

The researches already in hand have been brought into full activity, and a comprehensive programme for the future has been prepared. It is anticipated that funds will be available for a minimum expenditure of at least £16,000 per annum for State-aided researches, with provision for large extensions.

The researches initiated by the Institution, viz. Buried Cables, Insulating Oils, Insulating Materials, Magnet Steels, etc., are being continued under the control of the Committee and arrangements are in hand for a rapid extension of programme. Further important researches are already under consideration in connection with electric control apparatus, magnet steel, phosphor bronze, electric welding, overhead line wires, furnace carbons, and other matters.

(45) Electrical Development Association.

The Electrical Development Association, the formation of which was referred to in the last Annual Report as having been initiated by the Institution, has been successfully established, and is doing most important and useful work for the electrical industry. The Council earnestly hope that the Association will receive practical support from the Manufacturing and Supply sections of the Industry.

(46) Proposed Society of Radiographers.

The Draft Memorandum and Articles of Association of the proposed Society of Radiographers, prepared by a Committee consisting of four members nominated by the Institution, four nominated by the British Society of Radiologists and Physio-Therapists, and four Radiographers, have been approved by the Board of Trade. The principal objects of the Society are to ensure that only adequately trained radiographers are employed in electro-medical work and to promote the science and practice of radiography. It is expected that the organization of the Society will be completed at an early date. Full particulars will be published in the *Journal* in due course.

(47) Nitrogen Products Committee.

The Council were asked by the Ministry of Munitions in 1916 to nominate a representative of the Institution to serve upon the Nitrogen Products Committee which was then being set up to investigate the problem of the fixation of atmospheric nitrogen for the manufacture of high explosives, and also for the production of fertilizers during times of peace.

This Committee sat continuously from the autumn of 1916 until their final Report was presented in May 1919. This Report has since been issued as a Parliamentary Paper (Cmd. 482).

The Institution's representative was appointed Chairman of the Power Sub-Committee of the Nitrogen Products Committee, and a letter of appreciation has been received from the Ministry of Munitions acknowledging the services which the Institution rendered in this important work.

(48) Ministry of Transport.

In response to a request from the Ministry of Transport, the Council have nominated the following Members to represent the Institution on the Advisory Panels from which Committees of the Ministry are selected :

The President, Mr. Roger T. Smith.

Mr. Ll. B. Atkinson.	Sir John Snell.
Sir James Devonshire, K.B.E.	Mr. C. P. Sparks, C.B.E.
Mr. J. S. Highfield.	Mr. C. H. Wordingham, C.B.E.

(49) Annual Accounts.

Excess of Income over Expenditure.—After making full provision for contingencies there is a margin to the good on the Revenue Account for 1919 of £1,495 3s. 3d. This amount, which has been carried to the credit of the General Fund, compares with £1,270 11s. 5d. in 1918, an increase of £224 11s. 10d.

Mortgages.

	£	s.	d.
In the Accounts for 1918 these stood at	31,074	3	5
Amount of repayment during the year	875	18	0
They now stand at	30,198	5	5

Life Compositions Fund.—The total of the Fund on the 1st January, 1919, was £5,202 3s. 0d., and a further amount of £321 6s. 0d. was received in payment of Life Compositions during the year, a total of £5,523 9s. 0d. Out of this the sum of £109 10s. 0d. has been transferred to the General Fund, in accordance with the Articles of Association, on account of Life Compositions of members deceased during the year, leaving to the credit of the Fund £5,413 19s. 0d.

Building Fund.—This has been augmented during the year by—

	£	s.	d.
Donations, Subscriptions, etc.	17	10	0
Contribution out of Institution Revenue ..	858	8	0
	£875	18	0

which amount was applied in reduction of the Economic Life Assurance Society's mortgage, as shown above.

With the approval of the Auditors, it has been decided to merge this Fund into the General Fund, and effect has been given to this in the Accounts of the past year.

Assets.—Taking the Tothill-street Property and the Investments at cost, and the Institution Building and Lease, the Library and Furniture, etc., at the values standing in the books after writing off depreciation—

	£	s.	d
the Assets amount to	141,211	16	2
against Liabilities..	43,221	17	4
leaving a surplus of	£97,989	18	10

which is made up as follows :—

	£	s.	d.	
Life Compositions Fund	5,413	19	0	
Kelvin Lecture Fund ..	648	13	0	
Foreign Visit Fund ..	92	14	2	
Reserve Fund	11,000	0	0	
General Fund	80,834	12	8	
				97,989 18 10
This balance, in comparison with that of 1918, viz.				91,749 2 3
shows an improvement for 1919 of ..				£6,240 16 7

(50) Investment.

Since the accounts for 1919 were closed, a further £2,000 5¾ % Exchequer Bonds (1925) has been purchased by the Institution.

APPENDIX A.

Meetings.

The following is a list of the meetings held during the past twelve months :—

Ordinary Meetings ..	17	Engineers' Registration	8
Wireless Sectional Meetings	8	Finance	14
Informal Meetings ..	12	General Purposes ..	9
Council Meetings ..	18	Informal Meetings (and Sub-Committee) ..	8
Territorial Centres :—		Membership	9
Irish	3	Overhead Power Lines (and Sub-Committees)	4
North-Eastern ..	11	Papers	7
North Midland ..	4	Patent Law	8
North-Western ..	9	Research (and Sub-Committee) ..	2
Scottish	5	Ship Electrical Equipment	2
South Midland ..	9	Society of Radiographers	2
Western	4	Territorial Centres ..	2
Territorial Sub-Centres :—		War Memorial ..	2
East-Midland ..	3	Wireless Section ..	8
Liverpool	3	Wiring Rules (and Sub-Committees) ..	5
Preston	4	Other Committees and various Conferences	21
Sheffield	5		
Tees-side	8	Total.. ..	271
Students' Sections :—			
London	7		
Liverpool	4		
Manchester	6		
Newcastle	5		
Scottish	5		
Committees :—			
Benevolent Fund ..	6		
Electric Power Supply	4		

APPENDIX B.

Papers.

The following is a list of papers read during the Session 1919–20 :—

Papers read at Meetings.

Author.	*Title.*
W. Cross, Member.	Chairman's Address (North-Eastern Centre).
P. Dawson, Member.	"Overhead and live-rail conductor systems."
C. V. Drysdale, O.B.E., D.Sc., Member.	"Modern marine problems" (Eleventh Kelvin Lecture).
Capt. P. P. Eckersley.	"Duplex wireless telephony: some experiments on its application to aircraft."
Major K. Edgcumbe, R.E. (T), Member).	"The protection of alternating-current distribution systems without the use of special conductors."
A. Ellis, Member.	"Chairman's Address (Western Centre).

Papers read at Meetings—continued.

Author.	*Title.*
S. Evershed, Member.	"Permanent magnets in theory and practice."
Prof. C. L. Fortescue, Member.	"The design of multiple-stage amplifiers using three-electrode thermionic valves."
S. H. Fowles, Associate Member.	"Production of power from blast-furnace gas."
Dr. C. C. Garrard, Member.	Chairman's Address (South Midland Centre).
W. B. Hird, Member.	Chairman's Address (Scottish Centre).
Prof. G. W. O. Howe, D.Sc., Member.	"The high-frequency resistance of wires and coils."
D. M. W. Hutchison, B.Sc., Member, and W. J. Wayte, Associate Member.	"Electricity in tin mining."
Marius Latour.	"High-frequency machines."
A. E. McColl, Associate Member.	"Automatic protective devices for alternating-current systems."
L. Milne, Member.	"The electrical equipment of artisan dwellings."
R. Morton, M.D.	"The efficiency of high-tension transformers as used for X-ray purposes."
W. H. Patchell, Member.	"Notes on operating a by-product producer gas plant for power and heating."
C. C. Paterson, O.B.E., Member, J. W. T. Walsh, M.A., M.Sc., Associate Member, A. K. Taylor, Member, and W. Barnett.	"Carbon arcs for searchlights."
Major C. E. S. Phillips, O.B.E.	"Problems of interrupted and fluctuating currents."
Major C. E. Prince, O.B.E.	"Wireless telephony on aeroplanes."
J. A. Robertson, Member.	Chairman's Address (North-Western Centre).
Capt. H. J. Round.	"Direction and position finding."
Capt J. M. Scott-Maxwell, Member.	"Scientific management: a solution of the capital and labour problem."
W. M. Selvey, Member.	Chairman's Address (North Midland Centre).
J. Shepherd, Member.	"Failures of turbo-generators and suggestions for improvements."
R. T. Smith, President.	Inaugural Address.
R. Tanham, Member.	Chairman's Address (Irish Centre).
H. W. Taylor, Associate Member.	"Eddy currents in stator windings."
J. L. Thompson, M.Sc., Associate Member.	"Transformers for electric furnaces."
A. P. Trotter, Member.	Address to the Students' Section (London).
R. S. Wright, Member.	"High-tension transformers for X-ray work."

The following Lectures have also been delivered since the last Annual Report at meetings of Territorial Centres and Sub-Centres :—

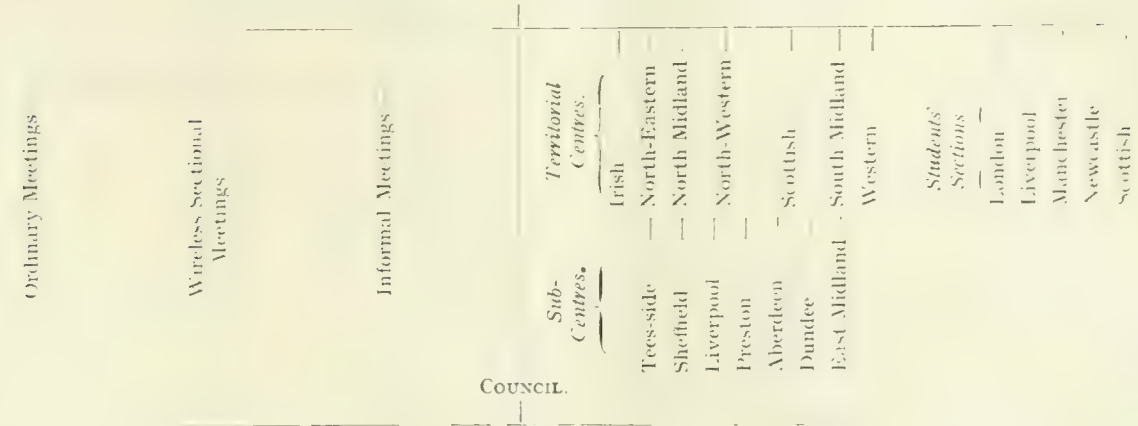
Author.	*Title.*
Lieut.-Col. F. C. Aldous, D.S.O., Associate Member, and A. E. Leigh Scanes, M.A.	"A critical survey of power supply in the Rhine Valley."
Prof. F. Bacon, Member.	"Thermionic valves."
L. H. A. Carr, Member.	"Some magnetic problems."
W. B. Lovell, Associate Member.	"Protective apparatus."
J. Lythgoe, Graduate.	"Electrical developments at Christchurch, New Zealand."
J. M. M. Munro, Member.	"Highland water power."
W. D. Owen, Associate Member.	"Wireless telegraphy in the mercantile marine."
W. Pearson, Associate Member.	"The Brush Ljungström turbine plant."
Major T. Rich, O.B.E., Associate Member.	"Electricity in the western war zone."
Prof. D. Robertson, Member.	"Electric clocks."
Dr. W. M. Thornton, Member.	"Electrical underwater signalling."
Dr. W. M. Thornton, Member.	"Foundations of the theory of electrical transmission of energy."
S. H. Webb, Associate Member.	"Housing and electricity."
T. P. Wilmshurst, Member.	"Electric power supply in the East Midlands."
C. H. Wordingham, C.B.E., Past-President.	"The electrical equipment of ships."
C. H. Wordingham, C.B.E., Past-President.	Address to Territorial Centres.
C. H. Wordingham, C.B.E., Past-President.	Address to Irish Centre.

The following papers not read at meetings have also been published in the *Journal* :—

Author.	*Title.*
A. E. Clayton, B.Sc., (Eng.), Associate Member.	"Magnetomotive force calculations for cylindrical-field alternators under steady short-circuit conditions."
A. B. Gridley and A. H. Human.	"Electric power supply during the Great War."
J. W. Meares, Member.	"The general principles of the development and storage of water for electrical purposes."
S. Neville, B.Sc.	"The calculation of tooth reluctance: a suggested improvement of Hird's method."
G. Stead, M.A.	"The short tungsten filament as a source of light and electrons."

APPENDIX C.

THE INSTITUTION OF ELECTRICAL ENGINEERS.



Committees. (*Standing.*)

- Examinations
- Finance
- Informal Meetings
- General Purposes
- Library
- Membership
- Overseas Information
- Papers
- Paul Scholarship
- "Science Abstracts"
- Ship Electrical Equipment
- Technical Co-operation
- Territorial Centres
- Wireless Sectional
- Wiring Rules

Sectional Committees.

- Electricity in Mines
- Electro-Chemistry and Electro-Metallurgy
- Lighting and Power
- Telegraphs and Telephones
- Traction

Committees. (*Special.*)

- Dutch Return Visit
- Engineers' Registration
- Model General Conditions
- Overhead Power Lines
- Patent Law
- Secondary Batteries Maintenance Agreement
- War Memorial

Bodies on which the Institution is Represented.

- Birmingham Chamber of Commerce
- Bradford Public Libraries Committee
- Bristol University
- British Engineering Standards Association
- British National Committee of the International Electrotechnical Commission
- Corrosion Committee of Institute of Metals
- Darlington Board of Invention and Research
- Duddell Memorial Committee of Physical Society of London
- Electrical Development Association
- Electrical Research Committee
- Engineering Training Organization Council
- Fuel Economy Committee of British Association
- Imperial College of Science and Technology, Governing Body
- Imperial Mineral Resources Bureau Conference
- International Scientific Unions
- International Illumination Commission, British National Illumination Committee
- Labour, Ministry of, Trade Advisory Committee for the Electrical Industry (Disabled Sailors and Soldiers)
- Leeds Civic Society
- Leeds Municipal Technical Library Committee
- Metalliferous Mining (Cornwall) School, Governing Body
- Munitions Inventions Department, Nitrogen Products Committee
- Munitions, Ministry of, Disposal of Surplus Government Property
- National Physical Laboratory, General Board
- Newcastle-on-Tyne Chamber of Commerce
- Radiographers, Society of
- Röntgen Society Advisory Committee for British X-Ray Industry
- Scientific and Industrial Research Advisory Council, Engineering Committee
- Scientific Societies, Conjoint Board of
- Technical Societies of Canada, Joint Committee
- Transport, Ministry of, Advisory Panel
- War Office Committee on Engineer Organization

THE INSTITUTION OF ELECTRICAL ENGINEERS.

REVENUE ACCOUNT FOR THE YEAR ENDED 31ST DECEMBER, 1919.

Dr. **EXPENDITURE.**

Year ended 31 Dec., 1918.		£	s.	d.	£	s.	d.
£ s. d.							
	To Management :—						
	Salaries and Wages (including Staff Provident Scheme and War Bonus) ...	7,236	6	10			
	National Insurance	11	2	6			
	Accountants' Fees	31	10	0			
	Printing	777	5	6			
	Stationery and Office Requisites	448	10	5			
	Addressing	43	16	6			
	Postage of Correspondence and Notices	469	12	7			
	Telephone	47	15	8			
	Travelling Expenses	50	18	6			
	Bank Charges	8	7	11			
5,796 19 9					9,125	6	5
	„ Institution Building :—						
	Ground Rent	2,201	0	0			
	Rates and Taxes	666	19	10			
	Insurance	126	10	10			
	Reserve for Repairs	400	0	0			
	Estate Agents' Fees	44	8	9			
3,255 7 4					3,438	19	5
1,127 17 11	„ Temporary Offices (No. 1 Albemarle Street) :— Rent, Lighting, Heating, Cleaning, etc....				1,175	11	11
1,369 3 11	„ Interest on Mortgages				1,379	1	7
18 16 0	„ Furniture and Fittings (Repairs and Renewals)				13	0	3
	„ Journal :—						
	Printing	3,241	8	9			
	Postage	678	10	8			
	Wrappers and Envelopes	176	10	6			
		4,096	9	11			
	Less Sales	700	5	10			
2,357 15 8					3,396	4	1
17 10 3	„ Lending Library (Books, Printing, Postage, etc.) ...				60	14	4
.7 0 0	„ Thompson Memorial Library :— Insurance, etc.				5	2	0
	„ National Service :—						
	Public Services, Coal Supplies, Postage, etc.	39	11	11			
	Electricity Supply Bill	72	1	10			
	Allowances to Members of Staff on Military Service	163	16	11			
628 2 7					275	10	8
——	„ War Memorial of Fallen Members (Printing, Postage, etc.)				99	8	2
	„ Science Abstracts :—						
	Salaries, Abstracting, Printing, Postage, etc....	2,858	14	1			
	Less Subscriptions, Sales, and Advertisements	2,104	7	11			
807 12 10					754	6	2
	Carried Forward				£19,723	5	0

Cr. **INCOME.**

Year ended 31 Dec., 1918.		£	s.	d.	£	s.	d.
£ s. d.							
16,344 2 2	By Subscriptions				19,532	1	4
1,146 1 6	„ Entrance Fees and Vellum Diploma Fees				2,311	1	0
44 2 0	„ Life Compositions				321	6	0
10 2 6	„ Donations and Subscriptions Towards Cost of Building				17	10	0
993 13 0	„ Dividends on Investments				1,357	14	4
62 19 6	„ Interest...				29	10	8
——	„ Street Lighting Specifications				0	15	2
	„ Institution Building :—						
5,865 10 0	Rent from Tenants				6,240	5	0
	„ Tothill Street Property :—						
	Rents from Tenants	884	15	0			
	Less Ground Rent, Repairs, Alterations Rates, Taxes, etc.	355	0	8			
369 15 10					529	14	4
24,859 1 11	Carried Forward				£30,339	17	10

REVENUE ACCOUNT—*continued.*

Dr. EXPENDITURE—*continued.*

				£ s. d.	£ s. d.
			Brought Forward	...	... 19,723 5 0
			To MEETINGS :—		
			Advance Proofs	143 14 6	
			Reporting	119 14 0	
			Grants to Students' Section	30 0 0	
			Honorarium to Lecturer	31 10 0	
			Refreshments, Assistance, etc.	146 8 4	
			Hire of Rooms	129 3 0	
396	19	2			600 9 10
			„ TERRITORIAL CENTRES :—		
			Money Grants	1,066 6 11	
			Travelling Expenses	495 9 10	
709	0	5			1,561 16 9
115	1	10	„ PREMIUMS FOR PAPERS	... ...	140 7 8
			„ SPECIAL GRANTS :—		
			Electrical Development Association ...	250 0 0	
			British Scientific Products Exhibition ...	52 10 0	
			Conjoint Board of Scientific Societies ...	50 0 0	
			International Electrotechnical Commission	187 19 6	
402	10	0			540 9 6
——			„ ANNUAL DINNER	... ...	110 2 10
——			„ CONVERSAZIONE AND RECEPTION OF MEMBERS WHO SERVED IN H.M. FORCES	... ...	858 8 5
15	12	6	„ SHIP WIRING RULES (Printing, *less* Sales)...	... ...	36 9 1
——			„ WIRING RULES (Printing, *less* Sales) ...	... ...	25 18 8
——			„ MODEL GENERAL CONDITIONS (Printing, *less* Sales)	... ...	5 12 7
			„ RESEARCH :—		
			Research Premium...	25 0 0	
			Electrical Research Committee	375 0 0	
245	10	0			400 0 0
14	3	0	„ LEGAL EXPENSES	... ...	10 10 0
84	9	5	„ MISCELLANEOUS EXPENSES	... ...	84 5 9
					24,097 16 1
44	2	0	„ AMOUNTS TRANSFERRED TO :—		
			LIFE COMPOSITIONS FUND (*per contra*) ...	321 6 0	
277	12	2	SINKING FUND (Premiums for Redemption of Cost of Building and Lease) ...	277 12 2	
5,000	0	0	RESERVE FUND (Contingencies and Mortgage Redemption)	3,000 0 0	
			GENERAL FUND :—		
			Obligatory Repayment to Economic Life Assurance Society :—		
			Donations and Subscriptions towards Cost of Building £17 10 0		
			Contribution out of Revenue 858 8 0		
839	16	7		875 18 0	
			Expenditure on—		
50	2	6	Books and Binding for Library ...	58 9 10	
			Museum (Instruments purchased from the collection of the late Sir William Crookes)	213 12 6	
1,270	11	5	**Balance of Revenue for the year 1919**	1,495 3 3	
					6,242 1 9
					£30,339 17 10

INCOME—*continued.* Cr.

	£ s. d.
Brought Forward	30,339 17 10
	£30,339 17 10

BALANCE SHEET, 31ST DECEMBER, 1919.

Dr. LIABILITIES.	£ s. d.	£ s. d.
To Economic Life Assurance Society :—		
On Mortgage of Institution Building (1909) ...	26,000 0 0	
Since repaid	7,301 14 7	
	18,698 5 5	
On Mortgage of Tothill Street Buildings and Site (1910)	11,500 0 0	
		30,198 5 5
„ Life Compositions Fund :—		
Balance at 1st January, 1919	5,202 3 0	
Life Compositions received in 1919	321 6 0	
	5,523 9 0	
Less Life Compositions of Deceased Members transferred to General Fund	109 10 0	
		5,413 19 0
„ Kelvin Lecture Fund :—		
As per last Balance Sheet		648 13 0
„ Trust Funds Capital Accounts :—		
Salomons Scholarship	2,126 19 3	
David Hughes Scholarship	2,000 0 0	
Paul Scholarship	500 0 0	
Wilde Benevolent Fund	2,586 19 2	
		7,213 18 5
„ Trust Funds Income Accounts :—		
Balances unexpended :—		
Salomons Scholarship	268 10 7	
David Hughes Scholarship	254 6 8	
Paul Scholarship	18 15 0	
Wilde Benevolent Fund	7 8 4	
		549 0 7
„ Foreign Visit Fund		92 14 2
„ Sundry Creditors		3,854 8 4
„ Subscriptions received in advance		310 6 11
„ Repairs Suspense Account :—		
Balance (as per last Balance Sheet)	771 7 8	
Amount set aside in 1919	400 0 0	
	1,171 7 8	
Less Expenditure on Repairs in 1919	75 10 0	
		1,095 17 8
Carried Forward		49,377 3 6

Cr. ASSETS.	£ s. d.	£ s. d.
By Institution Building and Lease :—		
Cost	73,028 6 10	
Less Reserve for Depreciation, being Sinking Fund Premiums paid	2,959 8 4	
		70,068 18 6
„ Sinking Fund (Premiums paid for Redemption of Cost of Building and Lease)		2,959 8 4
„ Tothill Street Buildings and Site (at cost)		19,260 17 1
„ Life Compositions Investments (at cost)* :—		
£2,600 Natal Zululand Railways 3% Debentures	2,270 12 0	
£1,500 Lancashire and Yorkshire Railway 4% Preference Stock	1,513 10 4	
£2,000 Assam Bengal Railways 3% Stock ...	1,548 0 6	
		5,332 2 10
„ Kelvin Lecture Fund Investment (at cost)* :—		
£694 16s. 9d. 5% War Stock		648 13 0
„ Trust Funds Investments (at cost)* :—		
Salomons Scholarship :—		
£1,500 New South Wales 3½% Stock	1,556 5 9	
£500 Cape of Good Hope 3½% Stock	570 13 6	
	2,126 19 3	
David Hughes Scholarship :—		
£2,045 Staines Reservoirs 3% Guaranteed Debenture Stock	1,998 15 0	
Cash at Post Office Savings Bank	1 5 0	
	2,000 0 0	
Paul Scholarship :—		
£625 4% Funding Loan		500 0 0
Wilde Benevolent Fund :—		
£875 Great Eastern Railway Metropolitan 5% Guaranteed Stock	1,493 16 3	
£215 North Eastern Railway 4% Guaranteed Stock	250 19 9	
£100 London County 3½% Stock	101 8 6	
£250 New South Wales 4% Stock	251 6 0	
£100 3½% War Stock	94 8 8	
£100 5% War Stock	95 0 0	
£381 15s. 1d. 4% Funding Loan	300 0 0	
	2,586 19 2	
„ Library (exclusive of the Ronalds Library and Faraday Papers, which are held in trust) :—		
As per last Balance Sheet	1,111 10 6	
Additions in 1919	58 9 10	
	1,170 0 4	
Less Depreciation (10%)	117 0 0	
		1,053 0 4
Carried Forward		106,536 18 6

BALANCE SHEET—*continued.*

Dr. LIABILITIES—*continued.* ASSETS—*continued.* **Cr.**

	£ s. d.	£ s. d.
Brought Forward		49,377 3 6
To Reserve Fund (Mortgage Redemption and Contingencies)		11,000 0 0
„ General Fund :—		
Balance at 1st January, 1910	31,442 13 8	
Life Compositions of Deceased Members	109 10 0	
Amount of Building Fund (as per last Balance Sheet) transferred to General Fund	46,362 18 5	
Obligatory Repayment to Economic Life Assurance Society	875 18 0	
Premium for Renewal of L.C.C. Lease	500 0 0	
Expenditure in 1919 on—		
Books and Binding for Library	58 0 10	
Museum (Instruments purchased from the collection of the late Sir William Crookes)	213 12 6	
Unexpended Revenue for 1919	1,495 3 3	
	81,058 5 8	
Less Depreciation (*per contra*) :—		
Library £117 0 0		
Furniture, Fittings, and Apparatus 106 13 0		
	223 13 0	
	80,834 12 8	

	£ s. d.	£ s. d.
Brought Forward		106,536 18 6
By Thompson Memorial Library (Contribution towards purchase)		1,000 0 0
„ Furniture, Fittings, and Apparatus :—		
As per last Balance Sheet	2,132 19 10	
Less Depreciation (5 %)	106 13 0	
	2,026 6 10	
„ Museum (Instruments purchased from the collection of the late Sir William Crookes)		213 12 6
„ Sundry Debtors		1,801 15 1
„ Insurance Premiums and Sundry Payments in Advance		423 18 3
„ Stock of Paper for Publications		33 2 8
„ General and Reserve Funds Investments (at cost)* :—		
£750 Western Australia 4 % Stock	730 8 3	
£750 Union of South Africa 4 % Stock	742 12 0	
£750 Madras and Southern Mahratta Railway 4 % Debenture Stock	738 15 6	
£35 East Indian Railway "B" Annuity	791 5 4	
£1,500 South Australian 4% Stock	1,494 10 6	
£5,250 5 % War Stock	4,987 10 0	
£2,000 5 % National War Bonds	2,000 0 0	
£19,375 4 % Funding Loan	15,500 0 0	
	26,985 1 7	
„ Cash in Hands of Territorial Centres on 30 Sept., 1919		171 19 10
„ Cash :—		
At Bankers'	1,998 7 5	
At Post Office Savings Bank (David Hughes Scholarship Trust Fund Uninvested Income)	0 2 3	
In hands of Secretary	20 11 3	
	2,019 0 11	
	£141,211 16 2	

JAMES DEVONSHIRE,
Honorary Treasurer.
P. F. ROWELL,
Secretary.

* The above values are subject to depreciation.

We beg to report that we have audited the Balance Sheet of The Institution of Electrical Engineers, dated 31st December, 1919, and above set forth, together with the annexed Statements of Account. We have obtained all the information and explanations we have required. In our opinion the Statements are correct, and the Balance Sheet is properly drawn up so as to exhibit a true and correct view of the state of the Institution's affairs according to the best of our information and the explanations given to us and as shown by the books of the Institution.

30th April, 1920.

ALLEN, ATTFIELD & CO., *Auditors*,
Chartered Accountants,
24, Martin Lane, Cannon Street, E.C. 4.

SALOMONS SCHOLARSHIP TRUST FUND (Income).

Dr.	£ s. d.	Cr.	£ s. d.
To Amount paid to Scholars in 1919	25 0 0	By Balance (as per last Account)	223 14 6
„ Balance carried to Balance Sheet	268 10 7	„ Dividends received in 1919	69 16 1
	£293 10 7		£293 10 7

DAVID HUGHES SCHOLARSHIP TRUST FUND (Income).

Dr.	£ s. d.	Cr.	£ s. d.
To Amount paid to Scholars in 1919	62 10 0	By Balance (as per last Account)	256 17 9
„ Balance carried to Balance Sheet	254 6 8	„ Dividends received in 1919	59 18 5
		„ Interest do. do.	0 0 6
	£316 16 8		£316 16 8

PAUL SCHOLARSHIP FUND (Income).

Dr.	£ s. d.	Cr.	£ s. d.
To Amount paid to Scholar in 1919	6 5 0	By Dividends received in 1919	25 0 0
„ Balance carried to Balance Sheet	18 15 0		
	£25 0 0		£25 0 0

WILDE BENEVOLENT TRUST FUND (Income).

Dr.	£ s. d.	Cr.	£ s. d.
To Amount invested during 1919 :—		By Balance (as per last Account)	23 3 5
£131 15s. 1d. 4% Funding Loan	100 0 0	„ Dividends received in 1919	82 8 3
„ Balance carried to Balance Sheet	7 8 4	„ Interest do. do.	1 16 8
	£107 8 4		£107 8 4

RESEARCH ACCOUNT.

Dr.	£ s. d.	Cr.	£ s. d.
To Expenditure on Research on Insulating Oils	122 18 4	By Unexpended Balance from 1918	281 10 7
„ Balance paid over to Electrical Research Committee	161 12 7	„ Interest	3 0 4
	£284 10 11		£284 10 11

PROCEEDINGS OF THE INSTITUTION.

644TH ORDINARY MEETING, 12 FEBRUARY, 1920.

(Held at the Institution of Civil Engineers.)

Mr. ROGER T. SMITH, President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting of the 22nd January, 1920, were taken as read, and were confirmed and signed.

Messrs. H. Pearce and H. K. Trencham were appointed scrutineers of the ballot for the election and transfer of members, and, at the end of the meeting, the result of the ballot was declared as follows :—

ELECTIONS.

Member.

Gresley, Herbert Nigel.

Associate Members.

Alabaster, Eric Osborne, Bt.-Major, R.E.
Allinson, Henry John.
Bennett, Charles Henry.
Briggs, Henry Stacpoole, Major, R.E.
Brough, George Hall, B.Sc.
Brown, David Hunter.
Brown, Harold Lawson.
Burnside, Evelyn Elmer.
Bush, Paul Francis W.
Calverley, John Earnshaw.
Cheetham, George Arthur.
Clifford, John Arthur H.
Darby, Stanley.
Drew, Roy Longley, B.Sc. (Eng.).
East, Alan Neville.
Eden, John Alfred.
Furnival, Edward Hordley.
Goulburn, Thomas.
Hawes, James Reginald.
Heys, Francis Samuel.
Hogan, James.
Holliday, Fred Parkinson, Major, D.S.O., M.C., A.F.C.
Jackson, Henry Bertram.
Jessop, Charles Hedley.
Jones, John Richard.
Kenny, John Aloysius.
Legge, James, B.Sc.
Lowe, John William.
McKenzie, James Patrick, Capt., M.C., R.E.
Mallett, Edward, B.Sc. (Eng.).
Mawby, Arthur Willders M., O.B.E.
Mercer, Richard, B. Eng.
Ogilvie, Gregor Macgregor.
Parker, Elwin Thorley.
Pearson, Ernest Middleton.
Pettigrew, Thomas.
Riley, Fred.
Robertson, Hubert.
Russell, Frederick George.
Scarborough, Ernest Alfred.
Shepherd, Harold Conway.
Sillar, Kenneth Graham.
Smith, William Henry.
Somersgale, Charles William.
Sowter, Robert John, B.Sc.
Sowter, William Ernest.
Thompson, Harold Haselden.
Tompson, Ernest Edward.
Turner, Ernest Frederick.
Vowles, Julian.
Whewell, Henry.
Wood, Reginald Helm.
Wood, Thomas Stafford.
Wright, Harry Rowland.

Graduates.

Burgoine, Harry.
Christie, John Mills.
Daggatt, Albert Andrew.
Evans, Thomas Powell.
Foulds, William.
Griffiths, William Henry F.
Hooper, Stanley Arthur V.
Jamieson, James.
Malcolm, George Duncan.
Pitcher, Arthur Edwin, Flying Officer, R.A.F.
Read, Sidney.
Ridgway, Henry Nelsey.
Royle, William Arden.
Taylor, George.
Wilson, James Rodney.
Windridge, Charles Edward.

Graduates—continued.

Students.

Alexander, Ronald.
Ashley, William Herbert.
Bacon, Douglas Charles.
Baddeley, Gilbert Francis.
Bailey, Garnet Savage.
Baker, Charles Hale.
Baldwin, Harold.
Barlow, Herbert Dudley.
Barriscale, Hugh Joseph.
Barron, Oliver Harold.
Barton, Thomas.
Bawtree, Edward.
Beech, Cyril John.
Berry, John.
Blance, Robert Sydney C.
Bridgwater, William Reginald.
Broadbent, Harold Ralph.
Brockbank, Robert Alston.
Capper, Frank Wilson.
Carter, Fredrick Charles.
Catto, William.
Chalmers, John Murison.
Clenowich, Alexander.
Colquhoun, James Browne.
Costin, Arthur William.
Cowan, George.
Crawford, Cecil George.
Crompton, Oswald James.
Darbysire, Clifford Thomas E. J.
Davies, Cyril Walter.
Dawbarn, David Inglis.
Dennis, Reginald Burton.
Dotchin, Norman.
Douglas, John.
Elford, Ernest Norman.
Emanuel, Charles William.
Fincham, Arthur Joseph I.
Firkin, Frank.
Foulkes-Roberts, Maurice Wynn.
Fox, Raymond Charles.
Frampton, Harold George.
Freeborn, Frederic Victor.
Fry, Eric Charlton.
Gamage, Joseph Edmund.
Ganapati, Salem Venkatramana.
Gaster, Abraham Emanuel.
Gibbons, Arthur John.
Gibbs, William Reginald.
Godden, Leslie John.
Godfrey, Percy Frederick.
Gwynn, William.
Hall, James George.
Hall, Maitland Haseltine.
Hall, William John.
Horowitz, Hyman.
Hosker, Austin Thomas.
Howarth, Thomas.
Hoyle, William Dickon.
Jones, Harold William.
Kieran, Charles Stephen.
Leyland, Arthur James.
Long, Frederick Henry.
Lowry, Leonard Powell.
McDonald, James.
McLean, Ian Kennedy.
Macqueen, Eric Nottage.
Manyam, Venkataram Subra.
Merfield, Donald Edgar.
Millard, William Clement.
Mills, Arthur A.
Montgomery, Alexander William.
Moore, Alfred Thomas C.
Moore, Robert James.
Morcom, Herbert Geoffrey.
Morton, Sydney H.
Murray, George Edgar W.
Murray, John, B.Sc.(Eng.).
Narayanan, Manakal Sundaralingan I.
Nash, Esca Hunt.
O'Brien, Brian.
Oldham, Thomas John F.
Palitch, Velyko A.
Patrick, Ernest Reginald.
Pennington, John Hawley
Perks, John Noel R.
Phear, Howard William.
Plascott, Vincent Leslie J.
Prado, Alberto.
Protheroe, John Richard.
Pye, Cecil Norman.
Ramsay, Cecil Graham.

Students continued.

Ramsdale, William Stanley.
Ranger, John Edward G.
Reeves, Alec Harley.
Ribeiro, Augusto.
Ryall, Leonard Ernest.
Sancto, Herbert Edward.
Sands, Wilfred Frank.
Scholes, William Parry.
Scott, Archibald John.
Sellen, William James.
Shaffer, Raphael, B.Sc.
Shearer, George.
Slack, Alvan Esmond.
Smith, Clifford.
Snowball, William.
Somerville, Thomas Bousfield.
Stapleton, Stanley John.
Stark, John William.
Stevens, Sidney George.
Stevenson, William.
Stobart, Claude.
Sundaram, Gangadhara.
Sutherland, Robert Alexander.
Tainsh, Cecil Asquith.
Tait, John Lowden.
Taylor, John Russell.
Terry, Harold.
Thavenot, Joseph Raymund.
Thompson, George.
Torrance, John.
Trevor-Roper, Ranulph Dacre.
Tumilty, Hugh Germain.
Turton, Leonard.
Underdown, John.
Vincent, John James.
Wade, Cecil Crosby H.
Ward, Edward Forest.
Warren, Stanley George.
Washington, Frederick Henry.
Watson, Hubert.
Weston, George Edward.
Wilck, Charles Augustus.
Wilkinson, John Reed.
Williams, Harry.
Wills, Maurice Alan.
Wilman, William Eric.
Wilson, George Hulbert.
Withers, Bertie.
Yeadon, Norman.
Young, Eric William.

Associates.

Henderson, Stanley, Capt., R.A.F.
Kahn, Henry Joseph.
McAllister, Robert.

TRANSFERS.

Associate Member to Member.

Bishop, Douglas Howard.
Downie, Fredrick Habler, O.B.E., B.Sc.
Gardner, Mostyn Randal.
Humphreys, Percy Harry I., O.B.E.
Jackson, Philip Sydney Edward.
Milne, Frederick Lautour.
Pope, Alexander.
Spencer, Christopher John.
Woodworth, Leon Byron.
Young, Arthur Primrose.

Graduate to Associate Member.

Beaton, Frederick George.
Entwisle, Gertrude Lilian (Miss).
Grant, Edgar George.
Nordwald, Louis.
Skevington, Francis Kerr
Stacey, Clarence John.
Walsh, Alfred.
Wolf, Edward Moses, M.C.

Student to Associate Member.

Goodswin, Douglas Cecil.
Hill, Frank Edgar.
Schroeder, Francis Frederick H., B.Sc. (Tech.).
Solomon, Thomas Henry, B.Sc.

Student to Graduate.

Atkins, Leslie John.
Bunt, Charles Lionel.
Castle, John Palmer.
Gosden, Richard.
Pledge, David Edward.
Shaw, Hugh Dunkerley.
Simpson, William.
Smith, Fred.

A paper by Major K. Edgcumbe, R.E. (T.), Member, entitled "The Protection of Alternating-Current Systems without the Use of Special Conductors," was read and discussed, and the meeting adjourned at 7.45 p.m.

7TH WIRELESS SECTIONAL MEETING, 18 FEBRUARY, 1920.

(Held at the Institution of Civil Engineers.)

Dr. W. H. ECCLES, Chairman of the Wireless Sectional Meetings Committee, took the chair at 6 p.m.

The minutes of the Wireless Sectional Meeting of the 14th January, 1920, were taken as read, and were confirmed and signed.

A paper by Major C. E. Prince, O.B.E., entitled "Wireless Telephony on Aeroplanes," was read and discussed, and the meeting adjourned at 7.35 p.m.

JOINT MEETING WITH THE ROYAL SOCIETY OF MEDICINE (SECTION OF ELECTRO-THERAPEUTICS AND THE RÖNTGEN SOCIETY, 26 FEBRUARY, 1920.

(Held at the Royal Society of Medicine, 1 Wimpole Street, W. 1.)

At the opening of the meeting at 5 p.m. the chair was taken by Dr. A. E. Barclay, President of the Electro-Therapeutics Section of the Royal Society of Medicine, and after an adjournment for dinner the meeting was resumed at 8 p.m., Mr. Roger T. Smith, President of the Institution, taking the chair.

The following papers were read and discussed and the meeting adjourned at 10.10 p.m.:

"The Efficiency of High-Tension Transformers as used for X-Ray Purposes," by Reginald Morton, M.D.;

"Problems of Interrupted and Fluctuating Currents," by Major C. E. S. Phillips, O.B.E.;

"High-Tension Transformers for X-Ray Work," by R. S. Wright, Member.

It was agreed that the discussion should be continued at another Joint Meeting to be held next Session.

645TH ORDINARY MEETING, 11 MARCH, 1920.

(Held at the Institution of Civil Engineers.)

Mr. ROGER T. SMITH, President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting of the 12th February, 1920, were taken as read, and were confirmed and signed.

The list of candidates for election and transfer approved by the Council for ballot was taken as read and was ordered to be suspended in the Hall.

The following donations were announced as having been received and the thanks of the meeting were accorded to the donors:—

Building Fund.—W. M. Mordey, A. R. Smith, Sir John Snell, H. W. Young.

Library.—The American Institute of Electrical Engineers, The British Engineering Standards Association, The Carnegie Endowment for International Peace, The Chief Canadian Government Trade Commissioner, The Signals Experimental Establishment (Chief Experimental Officer), The Department of Scientific and Industrial Research (Advisory Council), J. G. Hill, W. S. Kennedy, Dr. A. E. Kennelly, The Lancashire and Cheshire Coal Research Association, Messrs. Merz & McLellan, The Meteorological Office (London), The Munitions Inventions Department (Ministry of Munitions of War), Société des Ingénieurs Civils de France, Technical Publishing Company, Ltd., U.S.A. Department of Commerce.

Benevolent Fund.—See *Institution Notes*, No. 19, page 14, March 1920.

THE PRESIDENT: Many members are anxious about the Civil Engineers Registration Bill, which has been receiving the Council's attention, as well as that of a special Committee, for the last four months. Had the Institution of Civil Engineers persisted with their original proposal the Council had made arrangements to ascertain without delay the views of the members as a whole and to act accordingly. The original proposal was, however, amended, and the Council are continuing to discuss the matter with the Institution of Civil Engineers and other engineering societies with a view to arriving at a friendly settlement. Such negotiations are necessarily confidential and we cannot yet discuss details, but I wish members to know that their interests, together with those of the whole engineering profession with which they are bound up, have been our first consideration. The Council have had, and still have, no hesitation in refusing to accept as satisfactory the solution put forward by the Institution of Civil Engineers; and members may rest assured that the Council will oppose any solution that does not seem satisfactory. When a satisfactory solution is put forward, as I hope it may be, by all engineers acting together, the Council will consult members before committing them to it.

A paper by Mr. W. H. Patchell, Member, entitled "Notes on Operating a By-Product Producer Gas Plant for Power and Heating," and one by Mr. S. H. Fowles, Associate Member, entitled "The Production of Power from Blast Furnace Gas," were read and discussed, and the meeting adjourned at 7.40 p.m.

8TH WIRELESS SECTIONAL MEETING, 17 MARCH, 1920.

(Held at the Institution of Civil Engineers.)

Dr. W. H. ECCLES, Chairman of the Wireless Sectional Meetings Committee, took the Chair at 6 p.m.

The minutes of the Wireless Sectional Meeting of the 18th February, 1920, were taken as read, and were confirmed and signed.

A paper by Captain P. P. Eckersley entitled "Duplex Wireless Telephony: some Experiments on its application to Aircraft" was read and discussed, and the meeting adjourned at 7.35 p.m.

646TH ORDINARY MEETING, 18 MARCH, 1920.

(Held at the Institution of Civil Engineers.)

Mr. ROGER T. SMITH, President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting of the 11th March, 1920, were taken as read, and were confirmed and signed.

Messrs. C. F. Proctor and E. S. Harpham were appointed scrutineers of the ballot for the election and transfer of members, and, at the end of the meeting, the result of the ballot was declared as follows:—

ELECTIONS.

Members.

Angold, Arthur Ernest.
Birkett, Robert.
Bolton, Frederick.
Brooking, John Henry C.
Clinker, Reginald Charles.
Morton, James Arthur.
Osborne, Hugh.
Shoenberg, Isaac.
Thomas, George Nevil.
Watson, Henry Sinclair, B.A.

Associate Members.

Astley, John William.
Barker, Norman Humphrey.
Bhattacharji, Narendra Chandra.
Blades, Rowland Wrench.
Brent, Herbert Cyril.
Briggs, Ernest Edward.
Browne, Percival Arthur.
Burgess, Percy James.
Butcher, Herbert John.
Campbell, Ernest.
Chisholm, George Gordon.
Day, Frederic.
Dobbie, Charles Lizars.
Dupree, Frederick Henry.
Frazer, Walter A.
Garrard, James Alfred T.
Gillings, Charles.
Gresham, Charles Bernard
Haskins, Harry Clifford.
Head, Howard Clark.
Hegney, Valentine John.
Hopkins, William Dawson.
Hurle, Valentine Royal.
Hursthouse, Calvert Fearon.
Jeffery, Leslie Brownlow G.
Jenkins, George Wilson.
Johnson, Thomas Marius.
Jolliffe, Valentine Noices.
Lloyd, Charles Graham.
Maclean, Alan Douglas, B.Sc. (Eng.).

Associate Members—continued.

McPhail, Robert.
Moss, Harry.
Murray, Edward William.
Plevin, Percy Johnson.
Ramsden, John Scowcroft.
Rochester, Henry
Russell, Matthew.
Saddington, Charles William.
St. John-Browne, John Richard.
Shakeshaft, Frederick.
Symes, William Fitzroy, S.S.
Taylor, Frank David.
Townley, Duncan Campbell.
Turner, John.
Wallwork, Thomas.
Wilson, James William.

Graduates.

Athorn, Stewart John.
Beddall, Walter Samuel H., Captain, R.E.
Chesterton, Arthur James.
Cotsell, Geoffrey William.
Deshpandè, Shankar Balevant, B.A.
Eiriksson, Helgi H., B.Sc. (Eng.).
Elliott, Donald Sydney.
Ellis, Leonard George.
Emmett, Herbert.
Findlay, James Duffus F.
Gardner, Colin Hamilton.
Gillespie, Robert Purdie.
Higham, John Bellamy J.
Jack, John.
Menon, K. P. Padmanabh, B.A.
Minchin, Humphrey Noël.
Partridge, Margaret Mary (Miss), B.Sc.
Pougher, Arthur William.
Rettie, Charles.
Shallcross, Herbert.
Toon, Frank Joseph.
Turner, George William.
Westwood, Hugh.

Students.

Abernethy, John William A.
Alston, William Richmond.
Baruxaki, Leonard Alan.
Bassil, Richard Whitley.
Baxendale, Frank.
Bayliss, Carol William.
Biles, Reginald William.
Bond, Fred.
Bradford, George.
Burgoyne, Gerald Vere B.
Butler, Percy.
Calder, John Maxwell.
Clarke, Harold.
Cockcroft, John Douglas.
Colman, Stanley Fordham.
Cosgrove, Cyril Wilfred.
Cribbes, Robert Lamb.
Cridland, Charles Elliot T.
Cuffley, Walter.
Dance, Herbert Ernest.
Dannatt, Cecil.
de Steiger, Frederick Bernard.
Double, Hugh Stanley.
Drucquer, Leonard.
Eadon, Alan Theodore E.
Edwards, John Marshall.
Edwards, Leslie.
Ellams, William.
Fearnley, Ronald Arthur.
Friendship, Cyril Arthur.
Gabel, Reuben.
Gallon, William Anthony.
Gault, David M.
Hadfield, Tom.
Hallett, Harold James.
Harvey, Arthur Frederic S.
Haslam, George Eric.
Haylor, Leslie Jack H.
Hewitt, John Leslie.
Hollinghurst, Frank.
Hvistendahl, Herbert Selwyn.
James, Frank Leslie.
Johnson, Charles.
Johnson, Leslie John N.
Jones, Arthur Thomas.
Kelly, John Philip.
Ledward, Thomas Archibald.
Lepper, Cyril Herbert.
Lewis, Agnes (Miss).
Longmuir, James Bogie.
McCabe, Frank.
McCulloch, Kenneth Pearson.
McLean, Alfred Horatio.
Marsland, Sidney William.
Martin, Alexander McDuff.
Matthews, William Thomas.
Mayo, Charles Gilbert.
Melsome, Robert John.
Mines, Richard.
Moir, Roy Adamson.
Morgan, Arthur Edward K.
Morris, William Idwal.
Mortimer, Seth.
Munoz, Agustin.
Nixon, John Humphrey R.
Norton, Leopold Gerard.
Paterson, William.
Paton, Edgar.
Payne, Norman.
Paysant, Louis Charles.
Pettermann, René.
Picard, Edward Arthur K.
Rennie, Ronald James.
Rose, Victor.
Rowe, George Laver.
Semple, James Hamilton.
Sen, Ranajit Chandra.
Sevalho, Annibal.
Slattery, Lewis.
Smith, Bobs Redvers.
Stanley, Ernest Edmund.
Stobart, John William.
Street, Raymond Walter.
Thornhill, John T.
Trehern, Cecil.
Wadlow, Donald Leslie.
Walker, Charles Ian.
Weston, Cecil Burton.
White, Albert Ernest.
White, Francis William.
White, Richard Frederick.
Wilkinson, Leslie.
Williams, William Trefor.
Willson, Leonard Frank.
Winder, Arthur Thomas.
Wolfenden, John Thomas.
Wright, Charles Henry W., B.Sc.
Wulff, Lawrence Louis E.
Young, Henry Judd.

Associates.

Parsons, Charles Sidney, B.Sc. (Eng.).
Swain, John Henry S.

TRANSFERS.

Associate Member to Member.

Alexander, Robert Donald T., O.B.E., D.S.O.
Bedson, Noel Phillips.
Bennett, Cyril George M.
Brown, Sir Arthur Whitten, K.B.E.
Byng, Edward Stanley.
Coates, William Höjel C., M.C.
Evans, Llewelyn, Lt.-Col., C.M.G., D.S.O., R.E.
Fairclough, Richard Dawson.
Goad, David, O.B.E.
Johnson, Reginald.
Lock, Archibald Charles.
Mayson, Christopher Mark.
Mohr, Stanley Melbourn O.B.E., M.C.
Nadejde, Horia Ioan, M.Sc. (Eng.).
Nelson, William Muir.
O.Brien, Henry Eoghan, D.S.O.
Parkinson, George Reginald J.
Porte, Francis Carlile.
Seddon, Edwin.
Smith, William Blair.
Thorpe, Wilfred Bertram.
Tucker, Arthur Garnet.

Graduate to Associate Member.

Cope, Frederick.
Dawson, William John N.
Haddock, Vivian Otto.
Paul, Bangsidhari.

Student to Associate Member.

Buist, David Maxwell.
Cooper, Wilfred Windham.
Damant, Edward Lorraine.
Hyde, Cecil Lewis G.
Khan, Abdul Ghafoor.

Student to Graduate.

Coote, Charles Douglas.
Elmer, John Claude.
Freedman, Paul.
Garland, Cecil Clifford.
Golé, Sadashiv Mahadeo.
Hofman, Stanislas.
Kill, Ernest Frederick.
Mann, Herbert Clarence.

The adjourned discussion on the papers by Mr. W. H. Patchell, Member, and Mr. S. H. Fowles, Associate Member (see page 327), was concluded, and the meeting adjourned at 7.45 p.m.

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SCIENTIFIC MANAGEMENT: A SOLUTION OF THE CAPITAL AND LABOUR PROBLEM.

By Captain J. M. Scott-Maxwell, B.Sc., Member.

(*Paper first received* 12 *September, and in final form* 19 *November*, 1919. *Read before* The Institution, 11 *December, before the* Scottish Centre, 9 *December, before the* North-Western Centre, 16 *December, before the* South Midland Centre, 17 *December*, 1919, *and before the* North-Eastern Centre, 12 *January*, 1920.)

History of Movement.

The first attack of science against rule-of-thumb methods in industry was directed to the problem of finding the true solution of the various factors governing machine-shop practice. The late Dr. F. W. Taylor, of Philadelphia, started his epoch-making experiments in the autumn of 1880 and carried them on over a period of 26 years. A paper entitled "On the Art of Cutting Metals" was based on the results of this great research, which cost from £30,000 to £40,000. Dr. Taylor read this paper in December 1906, when he was President of the American Society of Mechanical Engineers. As he points out so carefully, he had the co-operation of many exceptional men, but to him is due the original idea and initiative, the determination that kept it going for 26 years, and that wonderful patience of the scientific mind which can wait so long, rather than disclose immature results.

While carrying out this work, many ideas were evolved connected with management. The first paper describing the fundamental idea of what is now called Scientific Management was read by Dr. Taylor in 1895. Its title was "A Piece Rate System: Being a Step towards Partial Solution of the Labour Problem." This paper explained the method of fixing rates by means of splitting a job into its elements, which Taylor called elementary-rate-fixing. It also explained his method of payment-by-result by means of the differential-piece-rate, which increases the rate per piece for high outputs. The great new fact was elementary-rate-fixing which is a basic principle, a scientific discovery. At the end of the discussion on his paper, Taylor shows the dullness, even of the expert mind, when a new and revolutionary idea is submitted to it in company with another idea of much less importance but with which it is already partly familiar. These are Taylor's words: "I am surprised and disappointed that the elementary-rate-fixing has not received more attention during the discussion. No better evidence could have been produced, however, of the crude and elementary state in which the art now stands, of determining the time to do work and of fixing rates, than that only one member of the engineering Society which is in closest touch with the manufacturers of the country should have most briefly referred to the matter, while 13 engineers have discussed at length the less important matter of what kind of piece work to use."

In 1903 Taylor gave another paper entitled "Shop Management," which has become the classic of Scientific Management, and describes his full system.

Adoption of the name "Scientific Management."—General recognition of the term "Scientific Management" is not yet 10 years old. Public interest in the subject of efficient management was first aroused by the action of the eastern railroads in the United States, which raised their rates because of increased costs, mainly due to higher wages. A public investigation was ordered which lasted about six months, Mr. Louis D. Brandeis acted as chief counsel in the interest of the traders and fought the railroads on the plea that if all the railroads adopted a system of management, which he termed "scientific management," a saving of one million dollars a day could be effected. He referred to the Taylor system of management. Late in 1910 a conference of American engineers interested in efficient management decided to adopt the designation Scientific Management, after discarding such terms as the Taylor System, Functional Management, Shop Management, Efficiency.

The word "scientific" seems to upset some people. To many the rôle of science is only an iconoclastic one,

the destruction of long-cherished beliefs. Science is viewed by them as materialistic in its aim and soul-destroying in its progress. Science is, however, the outcome of the struggle of the intellect in the search for truth, and it accepts no empirical data, no rule-of-thumb methods without full examination. It is very important to have a good name for a movement. "Scientific" is a good name, and Scientific Management is bound to become a great and important movement in industry and politics.

Mental attitude to Scientific Management.—Before the war the term was seldom heard in this country, and the few occasions when a British engineer had the temerity to use it almost invariably evoked scorn. Though Scientific Management is now seldom scorned by engineers, there is still—after the lapse of 24 years since Taylor's first "surprise and disappointment"—almost the same failure to grasp the great significance of the principle of Scientific Management.

The real cause of the strong opposition, is that Scientific Management is the first system to realize that the human factor must come first. This is a revolutionary idea to the capitalist, who still considers that he comes first. Scientific Management is revolutionary to the trade unions because it enables work to be accurately measured for the first time in the history of industry. To many socialists and social reformers it is also revolutionary because they think that it is better for the character of the worker that he should use his own initiative as to how the work should be done, even though he has only rule-of-thumb to guide him.

Origin of opposition.—From experience gained in public discussion of this subject, it seems to the present author more important to emphasize the significance of the main idea, without which the details of the system are useless. Engineers prefer, as a rule, to study details, but the author's excuse for dealing at length with the principles of the subject is that Taylor himself and the pioneers of the movement, who are all engineers, regard the new mental attitude which it makes obligatory as the very essence of the system. All the devices used in office and shop as means of efficient production they consider in the same light as mechanisms, i.e. of secondary and not primary importance.

In Samuel Butler's great satire, "Erewhon," he describes a people who had destroyed all machines because at a previous stage of their history machinery had reached such a high state of development as to get the upper-hand of man. Samuel Butler lived in the age when the owners of machinery preached the doctrine that its fullest exploitation was an unmitigated benefit to mankind; and it was the great abuse of the machine workers about three generations ago which gave Karl Marx the stimulus to develop his materialistic theory of civilization, which is producing so much strife and bloodshed in the world to-day.

Manufacture by machine is hardly a century old, and this past century of machinery inherited the traditions of the preceding centuries, which were evolved by the trader and not the producer. In classical and mediæval times the men of energy and initiative were traders or merchants. The early producers were usually small people with little spirit of adventure in them. It was the wonderful spirit of individual enterprise which pushed the English traders into Europe in the time of Queen Elizabeth, and the Merchant Adventurers of England exercised very great political influence in Europe at that date. British traders were the pioneers of the British Empire in America, Asia, and Africa. Because of this we are apt to think that the business of a merchant in itself has done these wonders, and we consequently tend to make a fetish of everything pertaining to it. The traders' ideal has always been to buy in the cheapest market and sell in the dearest. They risked much capital in the past and employed little labour, while their profits bore no relation to costs but were regulated entirely by supply and demand, excluding of course any misadventure. Engineering advance has changed everything, and now the big men are producers, but the prestige of the merchant is still maintained and also the prestige of those associated with him, such as the bankers, while the engineering profession, the creator of our modern wealth, does not yet enjoy the prestige that is its due.

Considering that our economic education is based on these old conceptions, is it any wonder that we have profiteering throughout the world? It is the business ideal of the trader to profiteer, i.e. to be guided solely by supply and demand. Supply and demand must of course always be taken into account, but the idea reversed. Merchants prefer a high profit on a small turnover. Production requires low profits on a large turnover. The merchant system restricted the supply and thus lessened the consumption in order to maintain or increase prices. The production system cheapens the supply in order to maintain or increase the demand and thus maintain or increase consumption. The merchant system favoured the wealthy, and developed aristocracies. The production system favours the proletariat and thus develops democracy. The merchant system at the best did not raise the status of the workers. The production system must continually raise their status by continually raising the standard of living. The confusion of these ideals is very great at the present time amongst all classes of the people, and until they are disentangled and the one set encouraged and the other controlled we are bound to have continual industrial trouble. It is necessary that our economic conceptions should synchronize with the facts. At present they are entirely out of step.

Attitude Essential to Industrial Progress.

In applying the principle of cheap production, it must not be confused with the act of buying commodities. Labour must cease to be regarded as a commodity, which is one of the worst legacies of the old system. Labour in the abstract may be a commodity, but in the concrete it is human life. Increased output and payment-by-result is the sound foundation on which to build, but it ought to include everyone, from the managing director down, and both these aims should be qualified by another—a better life for the worker. Scientific Management increases output, and because it can accurately measure the work done in terms of human effort, payment-by-result is the fair and natural sequel. It achieves this greater output

by lessening the task and raising the status of the worker.

Wide field of application.—Scientific Management affects the individual as a unit worker, the workers as a group, and therefore trade unionism, and it affects all industry in its relation to the Government and to the consumers, and thus involves the whole nation. Many may argue that Dr. Taylor never visualized such a wide field for its application, but this is not the case. That his vision of its final development was very wide I know for certain, because when discussing the subject with him at Philadelphia in 1912, he told me that he hoped for a time when there would be a Board of Industry similar to the Board of Agriculture which in America does an immense amount of research work, the results being given free to American farmers by means of travelling groups of teachers in special trains—an Agricultural College on wheels. Such a department would standardize the methods and times of all operations common to the whole or a great part of the engineering industry, and also other and less complex industries. Taylor realized, without any question, that the ultimate goal of scientific management was its application to all industry in the interest both of the producer and of the consumer, that is, in the interest of the whole of society.

Scientific Management and trade unions.—Dr. Taylor could see little ultimate use for unions in America because the relations between capital and labour were improved by the adoption of Scientific Management. His early fights had all been against the restriction of output and the consequent demoralization of the workers. Ten years ago, when Scientific Management won its first public recognition, the unions were thereby aroused and brought pressure to bear on the American Government. It was a political fight and Taylor was no politician. The Government had to give in, and since then Scientific Management is forbidden in any Government workshop in the United States. These facts explain to British employers and workers Taylor's feelings on this subject. His own words on this subject refute those who denounce him: "the labour unions—particularly the trade unions of England—have rendered a great service not only to their members, but to the world, in shortening the hours of labour and in modifying the hardships and improving the conditions of wage workers." Taylor was an idealist with the real interest of the worker, the industry, and the State at heart.

The better and further development of trade unions in Great Britain makes the situation in this country a much brighter one. I do not see how Scientific Management can progress at all unless the unions are included in its scheme. Progress will only commence in earnest when the labour leaders grasp the full meaning to the worker of the elimination of useless work, which will lessen the total burden of labour; and when they realize that the accurate measuring of work protects the worker from underpayment, and that the greater allround efficiency makes shorter hours and higher wages a just claim on the community.

Scientific Management versus common sense.—Some seek to belittle Scientific Management by saying that it is only applied common sense. Common sense is conservative and, on the whole, prefers the easy to the strenuous intellectual life. Once it becomes familiar with the discoveries or rather applications of science to the needs of humanity, it accepts these new developments as part of its common philosophy and thus passes verdict on them, as if it had discovered them. Common sense discovers nothing. Its function is to accept all that proves good for humanity. If Scientific Management is therefore considered only common sense, it means that this instinctive arbiter of our lives considers it to be good for us. If the instinctive sense of the few accept it, it is certainly not accepted by the common sense of the many, and especially the workers. The thinking part of the community have to fight until it is accepted by the majority in the same manner that they accept wireless telegraphy, aeroplanes, or any of the great achievements of science. Taylor's common sense and his unhappy experience both told him that something was wrong. His consciously directed intelligence, backed up by unusual patience and determination, solved the problem.

Evolution of the idea.—It is said that there is nothing new in Scientific Management. It is true that the idea of time study was thought of in 1834 by Charles Babbage, an English mathematician interested in machinery, but the time was not ripe for its development. Consider the history of the idea of the evolution of life. It starts in ancient mythology, appears in all the classical philosophies, down through the Middle Ages to our own day. We know that Dr. Wallace published a leaflet giving a brief outline of the theory of evolution before Darwin decided to publish the "Origin of Species." All these people only instinctively sensed that the idea of spontaneous creation was wrong. Science in the days of Plato and Aristotle was such a very little child that it could not solve the riddle. Scientific thought in the middle of the nineteenth century was sufficiently advanced to make it possible for Darwin, with immense patience and concentration, to produce a workable theory such as no philosopher or scientist before him had been able to do. Hence, although we know that the idea was thousands of years old, Darwin gets the full credit for the theory of evolution. Darwin worked in the field of animal life, but his theory is now applied to every branch of science and every realm of human thought. Much that he could not explain is now much clearer. Much that he taught has been misunderstood and much purposely misrepresented. To-day, after 61 years, the majority of people do not yet understand the significance of the phrase "survival of the fittest." Our modern education still fails to produce the necessary intelligence to enable the average man to realize that fittest does not necessarily mean best, and that in many cases the "survival of the fittest" means the survival of the worst elements in society.

Taylor is the discoverer of Scientific Management, just as Darwin discovered evolution. Taylor applied himself to industry solely, but his discovery has much wider applications. Taylor was handicapped by the very limited development of industrial physiology and psychology, and much therefore that was not

easy for him to solve is a little clearer now. Taylor has been misunderstood by friends and purposely misrepresented by enemies. He realized from the beginning that the craft knowledge of the skilled man, or the common sense of the unskilled, did not enable them to do their work in the best possible manner. He was not an intellectual theorist, studying at second-hand the experience of others and thus producing a theory of management to cure all troubles. He paid in very hard work for his experience, and starting from the place of the individual worker at the machine, and with continual and thorough scientific investigation, he built his system upwards. The author will endeavour therefore to describe it in the same manner.

Motion and Time Study.

What Taylor first described in 1895 as elementary-rate-fixing is now more usually called Motion and Time Study. Scientific rate-fixing involves three problems :—

(1) The analysis of the job into its elemental operations by means of an investigation into the best method of accomplishing the desired result.
(2) The execution of the job by a first-class man, with tools and equipment of the best possible, and the timing of each elemental operation thus carried out.
(3) The investigation of the factors of environment and nature of the work as it affects the physical and mental capacity of the worker.

This third factor has been called the "fatigue" factor, but a better word to adopt might be "rest" factor, as this factor is the period allowed for rest so that the worker will not be fatigued.

Where a job has already been performed in the usual rule-of-thumb manner, motion study always comes first. Where a new job is to be performed for the first time under the Taylor method, motion study or analysis may not be necessary, as sufficient data may already be in existence to give both the best method and the correct times. The process of fixing rates then becomes a synthetic one.

In the early days of engineering almost all progress was by the rule-of-thumb method. If a boiler burst it was made a bit stronger next time, and those with the best instinctive sense of such things naturally made the fewest mistakes and the greatest progress. Our engineering forefathers would have scorned the idea that science could so investigate and use the laws of force and the strength of materials as to make it possible to design a machine on paper. They imagined the problem to be too complicated for any such solution. Scientific Management applies to the expenditure of human effort the same principles that have been already applied to design with such marvellous results.

Scientific Management started in the machine shop, where it divides all work into two parts :—

(1) Work done by the workman.
(2) Work done by the machine.

Taylor had to concentrate first on the machine part, and, as I have already pointed out, this great work occupied him over a period of 26 years and was started in 1880 to find an answer to the three problems that every machinist must solve in some way or other, viz.

(1) What tools to use ?
(2) What cutting speed to use ?
(3) What feed to use ?

Taylor gives us 12 variables in the solution of these three problems, as regards turning work.

(1) Number of tools to be used at the same time.
(2) Size and shape of tools to be used.
(3) Use or not of cooling agent on tool.
(4) Life of tool before regrinding.
(5) Quality of metal to be turned.
(6) Diameter of work.
(7) Depth of cut.
(8) Machine feed.
(9) Machine speed.
(10) Cutting pressure on tool.
(11) Speed combination required to give correct cutting speed and the required pressure on tool to take the cut.
(12) Stiffness of the work.

The experiments consisted in keeping all but one variable fixed, and varying that one over the working range. As this data accumulated, Dr. Taylor states that he often felt completely baffled as to how to apply it and he invoked the assistance of some of the best mathematicians. He says "they all smiled when told that they were expected to solve mathematically a problem containing 12 variables, and returned the problem with the statement that it belonged distinctly to the realm of rule-of-thumb, or empiricism, and could be solved only by the slow method of trial and error."

The problem, however, was solved by Mr. Carl G. Barth, a Norwegian technical graduate, who joined Dr. Taylor in 1899. Mr. Barth invented a wonderful series of slide rules by means of which Dr. Taylor asserts that a good machinist "can double the output of a machine which has been run, for example, for 10 years by a first-class machinist having exceptional knowledge of and experience with his machine and who has been using his best judgment." He also adds that "on the average, this understates the fact." No more obvious example can be found of the value of applied science in eliminating unnecessary work. The direct saving of over 50 per cent is also indirectly increased by the great improvements in machine-tool design, tool steel, belt drive and everything affecting machine work, which arose out of these experiments.

The other part is to analyse the various movements of the man using the machine, and these can be subdivided into three parts :—

(1) Handling of tools.
(2) Handling of machines.
(3) Handling of material or job.

The first is the more important and represents about 75 per cent of the total time. The handling of the

machine comes next with, say, 15 per cent, and the job itself only requires about 10 per cent of the total time. Handling of tools involves fixing bolts, clamps, etc., on the job, putting tools such as drills, turning tools, etc., into the machine, and measuring the work with calipers, gauges, etc. Handling the machine consists of stopping and starting, changing the speed or feed, and any other adjustments of the machine itself. The times required to perform these various operations on any machine must be tabulated and arranged so that they are easily and quickly available, like the actual times for the machine work.

This may seem laborious, but is not more so than the collection of data regarding materials, etc., that is available to the designer. Most work can be reduced to comparatively few elements. The following example of this elemental process is taken from Taylor's paper on "A Piece Rate System."

Work done by Man.	*Minutes.*
Lifting job from floor to planer table	—
Setting work true on table	—
Clamping job to table	—
Removing clamps from job	—
Removing job from machine to floor	—
Cleaning machine	—

Work done by Machine.	*Minutes.*
Rough cut $\frac{1}{4}$ in. thick, 4 ft. long, $2\frac{1}{2}$ in. wide ..	—
Rough cut $\frac{1}{8}$ in. thick, 3 ft. long, 12 in. wide ..	—
Finish cut 4 ft. long, $2\frac{1}{2}$ in. wide	—
Finish cut 3 ft. long, 12 in. wide	—
Total	—

For a more detailed example see Appendix 1.

The author has given these particulars in some detail because of their great historical interest and because they are the foundation of the whole structure of Scientific Management. Machine work lends itself to the most obvious and at the same time highly scientific analysis, but the same principle applies equally to fitting, assembling, and all human operations. In fact, it would be almost as difficult for the science of chemistry to exist without quantitative analysis, as for Scientific Management to exist without elementary time study.

Motion and time study give the minimum time for the job under the best possible conditions with all rest pauses eliminated. Should a better machine or tool be designed, the new time for these new conditions is arrived at in a similar manner. The Taylor system does not demand the best known tools. Each factory must work with the best tools available to it. Taylor's method applies to the worst possible tools, but if an employer considers it good policy to use old and out-of-date machinery, he must pay more for his output, because the standard times will require to be higher.

Fatigue or Rest Factor.

The objective before us is to set "times" so that not only is there no overstrain at the actual time of operation and no loss of interest in the work done, but that there is no chance of physical or mental hurt resulting to the worker in the future from the work done to-day.

In this field of investigation we leave the province of the engineer for that of the physiologist and psychologist. Taylor and the early pioneers had practically no assistance in this direction, and not being experts in this field they had to work almost solely on common-sense lines. There was no possibility of the knowledge of detail in this direction that they, as engineering experts, had regarding the fixing of the standard-minimum time. It is not fair to damn the engineer for not being a doctor as well. The engineer has clearly outlined the position and differentiated all labour into two distinct parts, the one mechanical, the other physiological. It is up to the medical profession to concentrate on their part of it.

It is interesting to all who believe in scientific management that the Government and public opinion are at last waking up to the necessity for industrial hygiene. The Government, however, seem to ignore Taylor's discovery, either through ignorance of it or for fear of labour antagonism, and are setting to work on the vast subject of human labour without this scientific differentiation which is so essential to a sound understanding of the problem. I used to hope that motion and time study, if recognized by the Government and accepted by the trade unions, would bring about the scientific study of industrial fatigue as a necessary corollary and thus be the cause of humanizing industry. Interest has, however, been awakened in an entirely different manner. The ignorance of employers, and especially of the Government, which urged heavy overtime during the first years of the war, brought about abnormal fatigue amongst many of the munition workers. Because of this evil experience, the Government is now interested in industrial fatigue, and sooner or later the experts are bound to see that an accurate knowledge of fatigue will also demand the standardization of normal industrial conditions and the means of accurately measuring the human effort required to produce a certain result.

Industrial Fatigue Research Board.—In December 1917, at the instigation of the Secretary of State for Home Affairs, a Research Board was appointed by the Department of Scientific and Industrial Research and the Medical Research Committee jointly "to consider and investigate the relations of hours of labour and of other conditions of employment, including methods of work, to the production of fatigues, having regard both to industrial efficiency and to the preservation of health among the workers." "The duty of the Board will be to initiate, organize and promote by research grants or otherwise, investigations in different industries with a view to finding the most favourable hours of labour, spells of work, rest pauses and other conditions applicable to the various processes according to the nature of the work and its demands on the worker." "Reports embodying the results of these investigations will be issued from time to time and the Board look forward to receiving the help of employers and workmen in the industries which are studied and in appropriate cases representatives of both will be invited to serve as temporary members of the Board."

The Board, as constituted, consists of six medical experts, one being a psychologist. There are in addition four non-medical Government officials and three directors of large companies. The two distinct functions involved in this investigation and pertaining to the engineering and medical professions should not be confused, and from this point of view the constitution of this Board seems wrong. The employer members should belong to another Board of engineering and production not business-experts, and one-half of this Board should consist of representatives of the trade unions who must be men of actual first-hand experience. These two Boards would have quite distinct functions to perform, but, like all human knowledge and effort, they and their work must not be shut up in watertight compartments. The fullest possible collaboration and co-operation between both Boards would be necessary, probably all the time, but especially when each had made some substantial headway.

We do not employ doctors as rate fixers, why should we employ engineers to study physiology and psychology? At the best we engineers can only be amateurs at it. It will only produce another failure if common sense tries to solve a very technical subject of which it can have no expert knowledge. The principle of Scientific Management must be applied to all such matters. Functions must be diffentiated and not mixed up. The doctors and the engineers, both being technical experts, should understand the meaning of function. Why let the politician or Government official muddle us in this manner? Some reports have already been published, and No. 3, "A Study of Improved Methods in an Iron Foundry," is most illuminating in its details and extraordinary in its attitude. It describes "study of movements" and "system of payment," as has been described in this paper and originally described by Dr. Taylor in 1895; yet this Government report tends to make those ignorant of the details of Scientific Management imagine that it was originated by the managing director of this foundry in 1915. Dr. Taylor's name and the word "scientific" are not once used. Science has always prided itself in giving credit where it is due, as it is often the scientist's only reward. Credit is due to another successful application of Scientific Management, but why this conspiracy regarding its originator? Why the impression created by this report that it is an isolated case with little significance to industry as a whole?

Physiological research.—A most fascinating book on this subject is a translation (1918) of "The Physiology of Industrial Organization" by Professor Jules Amar, Director of the Laboratory of Physiological Research in the Conservatoire des Arts et Mètiers, Paris. This book will be a revelation to most engineers who are interested in the subject. It proves that the physiologists have solved many of the problems of investigation and have already invented the machines which make it possible to apply the results to industry.

There is no time to go properly into details in this paper, but a very brief description will be given of some of the more important developments fully described and illustrated in Professor Amar's book. Instruments have been invented for recording by means of graphs —like any recording electrical measuring instrument —the variation of muscular activity, for example, when filing metal (see Appendix 2). The same dynamographic instrument has been adapted to other tools and implements such as hammers, shears, joiner's plane, spade, wheelbarrow, etc. By means of these graphs an apprentice or unskilled person can be trained to work in the most efficient manner, i.e. with the least physical effort, also the work of experienced men can be checked and improved if below the best possible standard. The graphs show both the vertical and horizontal components of the muscular pressure exerted by the hands of the worker, and the respirations of the worker are simultaneously recorded, also the measurement of the quantity of oxygen consumed.

The quantity of oxygen used by the worker is an accurate measure of the human energy he has used up. This is calculated by means of the respiration gauge or eudimometer which measures the oxygen inhaled and exhaled. One litre of oxygen is equivalent to 4·9 calories, the large calorie here used being the quantity of heat required to raise the temperature of one litre of pure water from 0° to 1° C. During repose it is found that an adult expends, on an average throughout the year, 2,100 calories in 24 hours, just to keep his body going. The heaviest day of manual work consumes in addition 2,000 to 2,500 calories. Intense brain work, on the other hand, requires almost no calories.

Professor Amar says: "A man who expends 2,400 calories in 24 hours barely expends 10 calories more when he devotes himself to long meditations, resolves difficult equations, makes learned calculations, and in short, thinks for eight hours a day." The calorimetric chamber, with which such fine measurements can be made, was one of Mr. Carnegie's gifts and is said to have cost over £40,000.

In other experiments, actual fatigue can be temporarily produced and the blood circulation measured by means of the cardiograph (heart-beats), the sphygmograph (pulse), and the oscillometer (arterial pressure), which measures the highest and lowest pressures successively. All these graphs, which are called cardiograms, pneumagrams, tonograms, etc., can be compared with similar ones made during repose or normal effort. These examples do not exhaust the list of instruments already invented and perfected, but they are sufficient to indicate how much these French physiologists have already accomplished.

Four scientific laws have been established equivalent to the well-known laws of physics. The first three are called the Laws of Chaveau and the last is due to Professor Amar.

(1) The expenditure of energy is in proportion to the muscular effort of contraction, to its duration, and to the degree of contraction.

(2) The expenditure of energy required to perform a given amount of work diminishes in proportion as the rapidity of the muscular contractions increases.

(3) There is a most favourable effort and a most favourable speed for the performance of the maximum of work with the minimum of fatigue.

(4) A muscle returns more speedily to its condition of repose in proportion as its work has been more rapidly performed.

The author trusts that what he has said on the study of industrial fatigue will not be considered too lengthy in view of the fact that he considers these details to be beyond the function of the engineer. His idea in giving so much is to arouse the engineer's interest in what is not only a subject of vital importance and of engrossing technical and human interest, but a subject which directly affects his profession. The physiologist must have the fullest sympathetic support and practical assistance of the engineers, and these details will, the author hopes, show the engineer that the physiologist is very much farther advanced than the engineering profession realizes, and that he is really in a position to commence important operations at once.

Industrial Research Organization.

Industry should bear the expense of continual industrial research both in methods of work and in fatigue; and as all labour in the ultimate is so much alike, such research should, to prevent overlapping, be on a national scale, and should therefore be carried out by the Government with the help and co-operation of the employers' federations and the trade unions in each industry. There is an immense amount of investigation to do, and what little knowledge has been acquired has been still less applied. In the application, therefore, as we start almost from zero, a little will quickly make a great difference. The change in mental attitude alone will be an enormous gain to the community.

The setting of standard times would probably be done by specially trained experts representing equally the masters and men. This would be done for one entire industry such as engineering, assuming all conditions to be the same. Then each territorial district such as the Clyde, the Tyne, the Midlands, South Wales, etc., would decide if the local conditions were better or worse than the standard for the whole country, and this would give a local factor governing the national standard. This district factor would have nothing to do with the local cost of living, but only with the geographical and climatic conditions affecting the producing capacity of the workers.

In each works expert investigation—also by representatives of employers' federations and trade unions—would be required of the machines, lighting, heating, ventilation, management, in fact everything affecting the capacity of the worker to produce. This would give a shop factor for each individual works. The workers in badly equipped factories and with bad environment would be protected by higher rates and their employers would be thus penalized. Sweating would be impossible. These local adjustments would of course affect both the fatigue factor and the standard time. The times set for all work would be in accordance with the mental and physical effort required to perform the work, not necessarily under ideal conditions but under actual conditions, and such a system would always tend to make the actual approximate to the ideal. This organization for the expert investigation of national, district, and shop standards or factors follows the organization of the Whitley scheme, the essentials being that the investigators must be first-hand experts and their functions must not be mixed up. Such a scheme could be applied to find international standards of production and thus make more possible of accomplishment the Labour aims of the League of Nations.

Payment-by-Result.

With the best possible system of management, it is still necessary to give incentive to the worker if maximum output is to be obtained. Mr. Lloyd George recently (August 1919) announced that the Government intend to investigate profit-sharing as one of the essentials to better co-operation between capital and labour. The Federation of British Industries had just previously published a report condemning profit-sharing as popularly understood and advocating payment-by-result. Profit-sharing is proved unsatisfactory when scientifically investigated, and it is therefore regrettable that more time should be lost, travelling once again along this old cul-de-sac. The F.B.I. report contains the following statement:—

"If the system of payment by results is to become general, it is essential that employers should establish equitable systems for fixing piece rates, and that there should be some reasonable procedure for the sanctioning by an impartial authority of any adjustment which may prove necessary."

It seems evident from this that Scientific Management is not yet understood by the employers, and if this is so, why should we expect the Government to lead where our industrial experts fail? Without accurate measurement of work, payment-by-result is only a catchword.

The best incentive to steady and efficient work is provided by a payment to the individual worker as soon as possible after the job is finished. Where times are set by the Taylor method, few mistakes are made. Where the employers only have set the times, the men are allowed more time where the mistake is against them, but where it is against the employer it must remain. When both masters and men set the time, as I have already described, mistakes are still less likely to arise and can be easily rectified. With correct times it is not necessary to cut the rates as masters have always done on piece work, which behaviour on their part is one of the principal causes of the restriction of output by the men. With Scientific Management the masters do not require to protect themselves by elaborate premium systems which the men do not understand and which thus arouse their suspicion and antagonism. Taylor devised a differential piece-rate system, which was a cross between ordinary piece work and premium bonus. As already explained, he paid an increased rate above a certain minimum on which the ordinary piece-rate was fixed. The difficulty with the differential piece-rate is that rates as set by Scientific Management are based on the standard minimum time. Even with the fullest instructions the workers require some time to get out of the old inefficient method and become experienced in the new. Taylor's payment system penalizes them too much at the start, although

quite fair to them afterwards. Mr. H. L. Gantt, one of Taylor's first and foremost assistants, got over this initial difficulty by developing what he called the "task and bonus" system, which pays a bonus instead of a piece rate and, when the bonus is not earned, pays the standard time wages. I would point out that Scientific Management does not urge any special system of piece work or premium bonus. Any of them which provides incentive will do, but the simpler the better. Some imagine that premium bonus as we know it to-day is just the same as Scientific Management, but this is quite erroneous. These payment schemes increase the worker's wages and are thus used to produce incentive and get output at lower cost. They are devices, just as machines are devices, and Scientific Management always uses the best possible devices that are available, but any combination of these devices is not necessarily Scientific Management.

The share of the saving effected which should be allocated to the worker, must be determined by the employers' federations and trade unions. The probability is that the saving should be halved, and this is probably more on the side of the worker, because Scientific Management means greatly increased effort and intelligence on the part of the employer, as compared with the present state of affairs.

Attitude of trade unions.—The trade unions have always professed hatred of both piece work and premium bonus, but more especially the latter, as they think that the former gives the worker more control over his time. With Scientific Management making it possible to measure labour effort accurately, premium bonus gives more steady incentive than piece work, and thus means more output and more pay for the worker. The worker is guaranteed his hourly wages at the start, and if after reasonable time he does not come up to the standard and earn a fair bonus, he must be found other work better suited to him.

Scientific Management makes a study of the man and selects the best man for the job. It differentiates and grades labour, and that is another reason why the trade unions are against it. In the initial stages of the struggle against the employers the unions had to fight on the basis of the average man. Now that the unions have won full recognition in this country so that non-unionists are not recognized in negotiations between masters and men, it seems no longer a sound policy for the unions to continue to penalize their best men by maintaining a medium standard of work and pay for all degrees of skill and experience. Democracy is presumed to-day to mean the ultimate rule and reward of the average man, but unless it is willing to compensate its best men a bit better than the average, its progress will be inevitably slow. Democracy has now got control if it learns how to use it, and with control it can afford to take what appeared to be great risks in the earlier stages, and with great gain to itself.

Nothing that has been said regarding Scientific Management and payment by result entrenches on the right of the worker to fight for higher wages. Statistics show, however, that 50 per cent of strikes are due to local troubles, none of which should arise under Scientific Management correctly applied. The elimination of 50 per cent of strikes would still further reduce the remainder due to the general industrial atmosphere being so much the clearer.

Scientific Management ceases to deal with labour as a commodity subject to supply and demand, and consequently all employers should pay the same amount for the same service done, irrespective of whether their works are isolated in a country district or situated in a crowded town. The geographical situation of an engineering works should not affect the labour cost to the employer, as this at present affects prices and profits which are not geographical and thus gives unfair advantage. Likewise it should not affect the real earnings of the workers. This is allowed for now by different wages in different districts, so that in order to equalize costs and thus stabilize prices and profits, the employers in districts where living is cheaper and wages consequently lower would pay the difference from the average or highest rate into a common fund to be used for industrial research in the industry concerned.

Instruction of Workers.

After analysing the job, fixing the time, method of payment, and selecting the proper man, Scientific Management then proceeds to teach the man how the job should be done. The teachers are the best men picked out of the shop. This means therefore a better and higher class of job for these men, which will call on all their mechanical experience and also develop their characters by the tact, initiative, and ability they will require to instruct, assist, and handle the men on the job. A worker who has been instructed carefully and sympathetically in this manner will naturally be able to do better and more difficult work than under the present system. Scientific Management raises both the teacher and the worker to a higher level of intellect and character. The close contact of the worker with the more highly trained and intelligent instructor, and the knowledge and habits acquired by working in the best possible manner, are gains to him which will affect his mental attitude far beyond the confines of his job, no matter how simple it is. The consciousness that his efficiency and increased skill enables him to do more difficult work than he could otherwise do, increases his self-respect both as a worker and as a citizen. The improvement in his physical and mental welfare due to the elimination of useless work, and the transformation of the wattless component into useful work, greatly improve his power factor. The ability to do more work and better work with the same or less energy than previously required for inferior work, combined with the incentive of a higher reward, increases his power of concentration and consequently his interest in the work. Scientific Management creates interest and incentive—not monotony. It neither sweats nor stultifies the worker, but has a stimulating and tonic effect on his character.

The unions do not like all this because they think it lessens the value of craftsmanship and makes the employer less dependent on the skilled man. As a matter of fact, Scientific Management has the same tendency as the introduction of improved machinery. It

may temporarily displace labour, but ultimately it will mean the employment of as many craftsmen as we have now, and many more men recruited from them, with a higher training than is necessary under the present system. The tendency is to raise the standard of each individual all the way up from the lowest to the highest. Dr. Taylor held very strong views on this. He explained to me how once he had been severely criticized by his superiors because he had helped his best assistant to get another job in another company. They argued that he had lost the services of a good man. Taylor maintained that it was bad policy to keep any man at a job if he was capable of a bigger job. If it was not possible to promote him, a better job must be found for him in another company. By doing this he always had the complete confidence and loyalty of all his assistants and maintained their incentive, as they knew they would under all circumstances be rewarded according to their efforts. This is a great gain, greater than the actual loss of an individual grown too big for the organization. It is a gain to the individual, to the industry, and to society. It is the scientific spirit at its best, and no example could refute more strongly the statements of its opponents that Scientific Management is nothing but an allround degradation of the worker.

Shop Organization.

As Taylor specialized the work of the manual worker, so he specialized the shop and office organization on the same functional basis. Science can be applied to the financial and commercial sides of business, but Taylor concentrated entirely on the production part of it. The functional basis is a considerable departure from the old system with works manager, head foreman, assistant foremen, chargemen, and leading hands. Taylor split up shop management into eight functions because it is next to impossible to find one man with the necessary qualities and experience to exercise all or several of these functions, so he takes eight men and puts them each to perform a definite function. Four of these are located in the shop and four in the office.

In the shop we have what he calls the gang boss, the foreman responsible for preparing the job for the worker, getting out drawings, instructions, jigs, tools and material, everything the man requires, but who is not concerned with the actual work done on the job. This is attended to by the speed boss, who sees that the proper tools are employed and the best speeds, feeds, and depths of cut are used. The inspector is well known to us under our present system and is responsible for passing the quality of work before bonus is paid. Without inspection of results, Scientific Management is impossible. The fourth man in the shop is the repair boss, who is responsible for the maintenance of the machines. This system assumes the exercise of equal authority by each functional foreman, and to get over this division of authority it can be modified on what is called a staff and line basis, somewhat similar to modern army organization. One foreman is in authority and is assisted by others, each expert in his special functions.

Office Organization.

All possible clerical work is removed from the shop to the office as the qualities required by the shop foremen make bad clerks of them. The head and heart of the production system in the office is the planning department which, according to Taylor, has also four distinct functions. The order-of-work or route clerk makes out daily lists covering "the exact order in which the work is to be done by each class of machine or men." The instruction-card clerk issues all the necessary instructions to the workers. The time-and-cost clerk gives the men all information they may demand regarding times and rates, and collects from them data for the cost records. Lastly there is the shop disciplinarian, who acts as peacemaker between men and foremen and adjusts all disputes. The above is detailed for a machine shop, but it is more or less the same in principle for other departments and other industries.

Planning department.—It is easy to see where the old approximates to the new and where we are at present making progress along these lines. Planning departments have already come in some works, but many are in a rather embryonic state. The planning department has two chief functions to perform. The one which gives it its name requires much information to plan properly, and much energy and initiative actually to push forward production through all the various channels. The other function is the purely clerical one of keeping records. If a company has therefore no cost records or other reliable data, the first necessity is to get a cost system started. Even if the Taylor system of motion and time study cannot be adopted because of the attitude of the men, the ordinary rate-fixer will be necessary. The instruction part of the system requires collaboration with the drawing office and the shop foremen, also the exercise of much tact with the men. It is practically non-existent in our present system. The peacemaker has arrived, but we usually call him a welfare superintendent.

In this system therefore of functional management, there is nothing startlingly novel. Some will say there is nothing new at all in the office system; but there is. There is something more than planning necessary to success. The planning department must see that its plans are carried out. To quote Mr. Gantt—"The authority to issue an order involves the responsibility to see that it is properly executed." If there is a check anywhere in the process of production due to lack of men, machines, tools or material, it is up to the planning department to forestall that check if possible by seeing it in advance, and if this is not possible, to see that it lasts the minimum time, by altering the plan or hustling and assisting the departments at fault. The drawing up of a plan of work is comparatively easy and seldom produces results. It is the execution of the plan that determines the efficiency of the organization.

Some businesses lack almost any system. Others have systems which only plan, and once the plan is set in motion it is allowed its own time to overcome obstacles. Scientific Management plans down to the smallest detail, but, without the executive ability and

energy to carry it through, such planning becomes little but a useless burden to be carried. Scientific Management requires a more capable management and a better-trained staff. It is not a system which can be started by an expert and then left to subordinates to run. It demands men of initiative at the top, with broad views and sound judgment.

Reputed Failures of Scientific Management.

In many cases the pioneer experts found the masters more opposed than the men to Scientific Management. In some large corporations the experts exposed corruption, and the experts had to go and their system was damned. In other cases employers lacked the ability to carry on the proper system themselves and only retained part of the paraphernalia of management, which without the true spirit is worse than useless. Other employers adopted it only in part, as they were afraid of the increased establishment charges. No firm should attempt the introduction of Scientific Management, even with the approval of the men and the unions, unless the office and shop organizations have first of all been put into shape as has been outlined in this paper. Without this organization to assist the worker at all points, nothing but disaster will result from the attempt to increase output by means of Scientific Management in the machine shop and factory.

During the war the British Government pleaded for increased output, which with a limited amount of labour could only be achieved by increased efficiency. They placed big contracts on "time and lime." They paid anything in wages and restricted establishment charges to the minimum. The way to make profits was to have the highest possible labour cost and the lowest establishment charge, i.e. the minimum efficiency of labour. The Ministry of Munitions still refuse to recognize efficiency as a claim against excess profits, but claim the right to penalize the producer for increased establishment charges. The Government behaviour has helped to lessen output and increase costs in shipyards and engineering works, and in the coal mines almost all incentive has been destroyed. A great responsibility rests with the Government and their advisers.

Scientific Individualism versus Socialism.

The present individualist system is more strongly attacked now than it has ever been, and the Government has been the means of greatly discrediting it. The cry of the State Socialists is that the present system is inefficient and a failure. Labour knows very little about the difficulties of production organization, and nothing about sales and finance, and consequently it assumes there is little or nothing to know. It sees the result of the inefficiency of organization every day in the daily work, and the agitators do the rest. Remove inefficiency, raise wages, shorten hours, improve conditions, create incentive, and individualism will beat any form of socialism.

To quote Dr. Taylor: "Among the risks of a manufacturing business, by far the greatest is bad management. This risk arises not so much from the evident mismanagement, which plainly discloses itself through occasional strikes and similar troubles, as from the daily more insidious and fatal failure on the part of the superintendents to secure anything even approaching the maximum work from their men and machines." This "daily more insidious and fatal failure" is pre-eminent in most Government undertakings.

Is it our respect for material things that makes us accept the great economies in its use that science has made possible? Is it our ignorance and pseudo-respect for man that causes us to refuse the application of science to the economy of human effort, and thus condemns man to perform work of which from 50 to 75 per cent has been proved to be useless whenever science has been applied? Material things have still a stranglehold on humanity, and to those who live for materialistic aims the economy of labour only appeals from that vicious point of view. That may satisfactorily explain the prejudices of socialist and social reformer to Scientific Management, but it says very little for the long-distance mental vision of the intellectuals that they think it possible to build up their industrial Utopias while retaining rule-of-thumb methods in the workshop.

Guild Socialism seeks to raise the status of the working man by the methods of the politician. The word "committee" has become almost a magic one in these days. Whenever there is a difficult problem to solve, the Government appoints a Committee to investigate it. What a travesty of the truth it is to think of the late Coal Commission, for example, as a scientific investigation. It was one of the most glaring examples of how investigation should not be carried out. It was the negation of the scientific ideal.

We are ruled by opinion, and scientific fact is held to be of secondary value. The unscientific opinions of the majority are not the truth. Democracy is a theory of politics founded on payment by results. If the electorate are slack or foolish, they suffer; if wise, they are rewarded. Our politics are very rule-of-thumb, and until the people have knowledge in place of opinions and prejudices, the demagogue will always score over all who try to lead and not fool the people.

Scientific Management is condemned by the Guild Socialists as an industrial bureaucracy which destroys the freedom and responsibility of the workers. How can the endless discussions of innumerable committees gain greater freedom for the workers when the performance of utterly useless work in the shop is considered to be an essential of such freedom? How does the execution of work in the most efficient manner lessen the responsibility of the worker? Unless democracy is able to evolve an expert bureaucracy which it will be able to control as its servant, and not suffer it to become its master as at present, then the payment of democracy will be suffering and that ultimately means revolution. Industry is a simpler field than politics, and it is therefore easier to arrange the necessary safeguards, which have been described above and which will ensure that those who carry out Scientific Management are the servants of an intelligent democracy of labour. Individualism, directed by the scientific knowledge of experts and recognized as such by the educated intelligence of the workers, will carry civilization more quickly to a higher plane than socialism

based on discursive and rule-of-thumb methods of production. Further advance will be by knowledge gained in the laboratory and the application of the scientific method throughout the whole realm of human effort.

Conclusion.

In 1819, a century ago and four years after Waterloo, this country reached its lowest point of misery. In spite of that, and due to the invention of machinery, we became the greatest producing country in the world. We shall probably reach our lowest point in less than four years from the Armistice, but it is not likely that the invention of machinery will save us this time. Our prosperity a century ago was due to the fact that other countries did not have machinery. Now it is common to the civilized world, and our prosperity will depend on our ability so to organize human effort that we shall be able to produce more with less labour. Material wealth must no longer increase the power and comforts of the few: its justification must be the amelioration of the lives of the many. We fail to distinguish between wealth and our attitude towards it. We cannot have too much wealth if we will only consider it of secondary importance. It is because there is too little wealth and not too much that so many abuses have arisen. The orthodox view of life is that character is developed by means of work, and there is no qualification that it must be efficient work. We must surely agree that some work, even if efficient, cannot by its very nature develop the intelligence and the character to the same extent as other work. Granted this, we must agree that a great amount of manual labour and clerical work is in this category, and once we have the honesty to face this fact, we see that the ideal of raising the worker's outlook by means of his work is very often not possible. The way to raise the social status of these workers is to reduce their working hours and pay them more, and thus give both the opportunity and the means to become better educated and live better lives. The philosophy or religion of work—that work in itself is good for one—belongs to the upper and owning class, and why should we be surprised that the working class does not believe in it? Our present system, being very inefficient, can give leisure and opportunity for culture only to the few. If democracy is to win against anarchy, it must win leisure and opportunity for the many.

Labour leaders emphasize the waste of human life through industrial accidents and bad conditions, but they fail to realize that the waste of human life because of inefficient work is far greater in its total result. They not only fail to see this waste of life, but by their teachings and action do everything to maintain it, actually arguing that the elimination of this waste would be bad for the worker.

It is because we are now struggling for something better, that production must be made so much more efficient, so much easier for the workers. It should be possible to produce material wealth so easily that it will cease to have its present inflated value, and the amount of wealth owned will cease to be the measure of the man.

History is not necessarily progressive in its sequence. One system is not displaced by another because the new system is better, but because the old is bad. There is no guarantee that once a system has been destroyed that it will be replaced by something better. The socialists say that because the present system means profits to private individuals the workers will not and should not become more efficient, and they claim similarly that if the nation or the producers, or both owned everything, the workers would then willingly become more efficient because the profit would go to the whole community. These are expressions of opinion disproved by what experience we have, and as long as opinions have the upper hand of facts, because of the inability to distinguish the one from the other, so long will the unscientific attitude dominate the country, and we must continue to pay for so many mistakes which would never be committed if the scientific attitude were developed in the Government and the people. The war record stares us in the face, and still we continue the same method. The socialists are beginning to realize the significance of Scientific Management and are bringing all their batteries to bear on it. This is a time when ideas are being quickly changed all over the world. A great responsibility rests with every member of a scientific profession to see that the truth prevails and that the demagogues, whether they be politicians or labour agitators, do not gain too much advantage from this abnormal state of mental flux, so that prejudice and mere verbal opinion do not triumph over scientific knowledge.

The British people have the traditional habit of belittling themselves by exaggerated accusations of incompetency, which the rest of the world seem to take at their full face value. This habit of depreciation has a very bad psychological effect on ourselves. It creates a disinclination to tackle boldly a big problem in a big manner. It took us as a nation a long time to visualize the ultimate size of the war and our time-lag in that respect made it last so much the longer. The war is over and we have a tendency to react again to little things, or the tackling of big things in little ways. We seem to lose again our courage and our vision. Never in all our history have we enjoyed the world prestige that we do now, and never have our responsibilities been so great.

This country is faced with the following dilemma. How is the population of the British Isles, which is less than one-half that of the United States and about three-quarters that of Germany, going to produce enough capable young men for the administration of India, Egypt, Mesopotamia? How are we to supply young engineers to execute the endless tasks waiting in these countries, not to speak of the allurements of our self-governing Colonies? How are we to do all this and at the same time maintain our supremacy at home, which is the foundation of it all? There seems only one way to guarantee the supremacy of the Mother Country, and that is to make industry and life at home greater and more fascinating than it is abroad. Industry must be so organized as to attract the attention and hold the interest of the very best and most efficient amongst us—those with the highest conception

of social service. To make industry a very much better means to a higher culture and to give the captains of industry a far greater part in the development of that culture instead of at present being completely immersed in the production of the means is a revolutionary idea which makes a strong appeal to the younger generation.

Scientific Management is a higher and more complex type of management and requires greater discipline and intelligence from everyone. We are the most disciplined of peoples, which does not mean the autocratic form that Germany tolerated and suffered under, but the self-discipline of a free democracy. Scientific Management is only advisable and possible in a community of free people. Don't let us be afraid of it, and while believing in it, tackle it by small and secret methods. Let us proclaim it widely and fight for it openly by every fair means. We are probably the only people who can tackle it on a national scale. Nothing short of a national movement, involving capital, labour and the Government will achieve what is required. It is a very big thing that we have to do.

One of our greatest national assets in the present difficult times is the advanced state of British trade-union organization. Do not let us belittle it or fear it. We lead in this direction and the most advanced countries follow us. The British working-class has produced many men of whom we have every reason to be proud, and, in spite of all we hear to the contrary, the mass of the workers are sound and will respond quickly to an open and honest policy of education and leadership. The war has tried our young men of all classes and they have not been found wanting. The present situation requires the faith, the courage, the optimism of youth to overcome the forces of reaction, whether on the extreme right or left of the industrial and political army. Give the younger generation more scope, encourage them to think and act in these matters, and the country will win through more quickly. We have in the stable and industrious character of our people a far greater asset than we can ever have in the most ingenious machines. If we realize that fact in time, the history of Great Britain in the 20th century will eclipse all its previous history in its progress towards a higher culture and a better life for all.

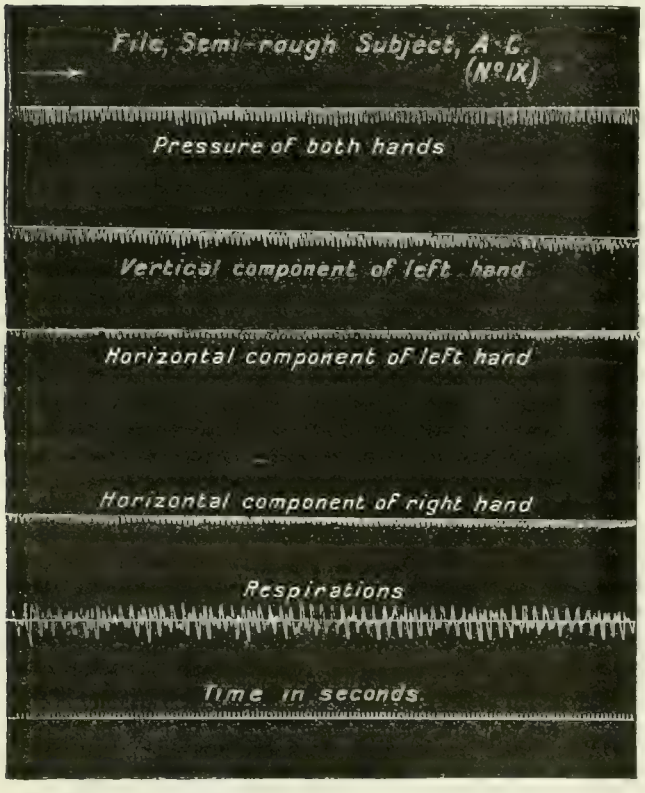
File, Semi-rough Subject, A. C. (No IX)
Pressure of both hands
Vertical component of left hand
Horizontal component of left hand
Horizontal component of right hand
Respirations
Time in seconds.

Fig. 1.

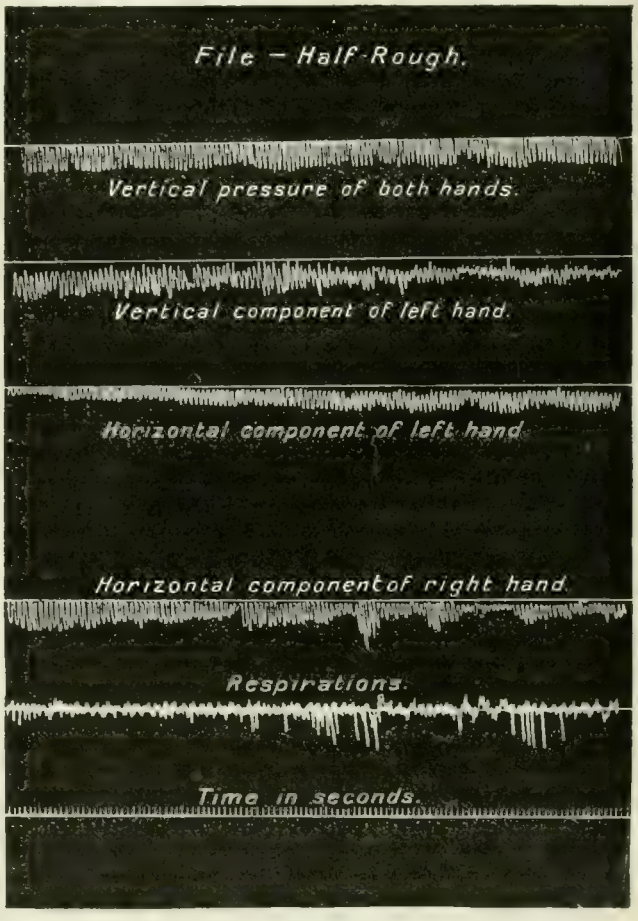

Fig. 2.

APPENDIX 1.

Instruction Card for Operation.

Symbol $1PLV_3P$.

1 *Sheets. Sheet No.* 1. *Drawing No.* 6601,105. *Machine No.* L10. *Order No.* PLVP.
Material, Steel. Class No...... *Pieces in Lot,* 400. *Time for Lot,* 393·61. *Bonus*.....

Description of Operation: Drill and Cut Off.

Item	Detailed Instructions	Feed	Speed	Element Time per Piece	Time for Entire Lot
1	Change Card				2·00
2	Learn what is to be done				2·00
3	Change jaws to $\frac{1}{2}$				0·91
4	Put collar on stock				0·19
5	Put stock in spindle and adjust collets				0·59
6	Set stop for length				0·31
7	Put CCCE $\frac{5}{8}$ in. in turret head				0·31
8	Put DDTS 3/16 in CCCE $\frac{3}{8}$				0·22
9	Set stop for DDTS 3/16				0·31
10	Put in PATL tool and set				0·77
					7·61
11	Set stock to stop			0·15	
12	Turn turret and start machine			0·08	
13	Drill 3/16 hole, 3/16 run	HF	5·36 1F	0·14	
14	Turn turret			0·08	
15	Cut off piece and round corners with file	HF	1F	0·12	
16	Put piece in tote can			0·02	
17	Count every 100 pieces. Time per piece=			0·02	
				0·61	
	90 per cent on handling time, 0·35			0·32	
	10 per cent on machine time, 0·26			0·03	
	Disassemble, 2·00			0·96	
	Time for lot = (number of pieces × 0·96) + 2·00 + 7·61				
	Time for 400 pieces = 393·61				

The use of symbols will be noted in the above example. Taylor and most of his followers put considerable stress on the necessity of using symbols to the maximum extent and based, as much as possible, on the mnemonic principle. These symbols, they claim, are quickly memorized by everyone using them, and greatly reduce the time and space required in making written instructions, while at the same time increasing their definiteness.

APPENDIX 2.

The accompanying illustrations (see page 340) from Professor Amar's book form a most interesting example of how practice can be examined and checked by applied science. Fig. 1 shows the manual effort expended by an experienced workman when filing metal. Fig. 2 shows the great amount of useless effort put forth by an inexperienced worker when performing the same task.

By means of diagrams, pictures and the cinematograph, the best methods can be quickly demonstrated to many workers. The present system of training is very slow and there is no guarantee of efficient results.

APPENDIX 3.

Bibliography of Scientific Management.

An extensive literature now exists, and the following list gives some of the books on which the paper is based.

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* These papers in the *Transactions of the American Society of Mechanical Engineers* are reprinted in "Scientific Management," by C. B. Thompson.

DISCUSSION BEFORE THE INSTITUTION, 11 DECEMBER, 1919.

Mr. L. B. Atkinson: The author has covered in the paper a very wide field, and it would be impossible for me or any other speaker to touch on all the points raised. Consequently I intend to confine my remarks to one aspect of the question, which I think is perhaps the most important one to be solved first. The question of time study and of the relation of fatigue is no new one to me, because as long ago as 1900 I carried out in a particular factory making hollow ware goods, without knowing of Taylor's work at that time, a large number of stop-watch trials over a very large number of processes without calling the attention of the workers to the fact. I plotted the cost of those against the total cost of running operations where there were furnaces and expensive machinery at work, in order to see what payments I could economically afford to make to the workers if only I could get large outputs from them. It is rather significant of the attitude of employers at that date that those with whom I was working on the Board, disregarding that at those outputs they were getting a lower cost per article, thought only that it would upset not only the whole of their own works but the whole of the district to pay the men at rates which gave them £4 or £5 a week. I do not propose to-night to deal with Taylor's work, but to direct my remarks more to the second title of the paper—the "Solution of the Capital and Labour Problem." I think the author has really not indicated where that solution arises directly from the work of Taylor as set out in the paper. He has, however, quite frankly recognized that no progress will be made in this subject unless those who are interested can carry with them the goodwill and co-operation of both organized and unorganized labour. Consequently I think the question to which we must address ourselves—I do not say to-night—in regard to Scientific Management (a phrase which I do not like) is: How are we going to get the co-operation of the workmen so as not to be continually fighting over the labour question? Why is it that workpeople object to Scientific Management? If we ask them they will give us the answer in different ways and not always very clearly, because they do not bring themselves to the point of putting it into words; but I think the objection of the ordinary worker can be put like this. He would say: "If I, as a worker on any operation, have the method planned for me it will not save *me* any work"—it is *himself* he is speaking of—"and although there will be a larger product *I* shall not get any more of the product than before." That is what the individual worker will say. It is what the trade-union leader will say, and it is what organized labour will say. What we have to do is to answer that question. Can we convince the individual worker that *he* will do less work, and that *he* will get a greater product than he has been in the habit of getting before? The workman of to-day has it firmly established in his mind that, so long as industry is conducted on a basis of private profit, any increase in the rate of production will augment that profit, but will not diminish *his* total work nor increase *his* total share of the product. It is not, in my opinion, sufficient to state in general terms that if there is a larger product everybody will eventually get more, because it is not even economically true. There may be a larger product, but it may be distributed in various ways, and so that is the question to which we eventually have to address ourselves if we are going to carry the workpeople with us in Scientific Management. We are told that Taylor spent £40,000 on his researches in the cutting of metals. I should think that the industries of this country have spent during the last year or two £40,000,000 in haphazard endeavours to settle this labour question. I believe if this Institution, or a group of Institutions, really tackled the problem it is quite possible a scheme could be devised by which we could get the co-operation of the organized labour of this country, to study the problem and to educate the general body of workpeople up to the point of realizing the importance of a larger product, and further to formulate some principles as to a reasonable way of dividing the increased product. That is the point to which I think all thinkers should first direct themselves. The details of the question of Scientific Management may follow. I will add that in my opinion the time is now ripe for such an effort. There are the Joint Industrial Councils in many industries, and they are having a great effect by giving very free opportunities of conversations and exchange of views on all sorts of subjects between the leaders of organized labour and the leaders of industry. I am quite sure the matter could be ventilated and discussed in those bodies, and that by utilizing them we can arrive at a solution

which will carry organized labour with us in the effort to increase production.

Mr. S. Mavor: The great problem before the country at the moment is that of production, and the system described by the author is very closely allied to that subject. The root of the problem is elimination of waste; the analytical method is devised to eliminate waste of time and waste of effort. The amount of wasted time in ordinary engineering establishments is greater than most of those in control realize, and it is by time analysis of processes and operations that the nature and extent of the problem can best be ascertained. As is well known, the rapid progress of electrical engineering and of the electrical industry generally has been due to the ease and precision of measurement. This system is the application of time measurement, and by this method immense economies may be effected. The responsibility for increased production lies less on the workmen than on the employer and on the management. The possibility of the worker increasing his output is limited; he may, if paid by results, double his output. But the possible increase of production by standardization, by improved organization, and by provision of properly devised machine-tool equipment is immensely greater than the possibilities by increased effort of the workmen. This method of time study is one that guides the management in the directions in which improvement can be made. During the three years of our shell production I used the Taylor time study on every operation, and I can testify that the results were most illuminating and educative. At the bottom of page 332 the author refers to 75 per cent of the total time being occupied in the handling of tools, 15 per cent in the handling of machines, and 10 per cent only in doing the actual job. That only 10 per cent of the machine time is employed in doing the actual job may be startling to those who have not conducted investigations on these lines, but it is quite credible; taking the average machine shop, it is probably more favourable than the truth. The proprietor of a large engineering works told me a little while ago that he had made an investigation of his own works and found that the machine tools in his machine shop were actually cutting during only 7 per cent of the total working hours of the machine. That illustrated the enormous margin which remains for increasing production by Scientific Management—I dislike the term as Mr. Atkinson does. The author has referred to the possibility of this system being imposed upon us by the Government. I altogether dislike such a suggestion. It seems to me that what we have to do is to educate first of all the employers, and secondly the employees. I believe that one of the root reasons—perhaps the root reason—for the present "ca' canny" practice is the fear of unemployment. That fear is well-grounded; workpeople have had bitter experience of unemployment and they believe that the more rapidly they produce the sooner they will be out of employment. This belief is of course a delusion, but until a satisfactory scheme of unemployment insurance is forthcoming, there will be a tendency in many workmen to nurse their jobs.

Mr. R. W. Paul: I regard the method adopted in the paper as unscientific, because it confuses work and effort; on page 336 the author states that Scientific Management makes it possible to measure labour effort accurately—it does nothing of the kind, being founded on payment by time. As a matter of fact, what we want and are willing to pay for is the expenditure of nervous energy; some workmen, by taking thought, double their output, even with reduced effort. To profit by the experiments of Professor Amar, dealing with muscular effort, is the business of the workman, who should cure himself of the habit of working like an amateur. Are we to pay for effort or for results? The firm wants, not the sum of the efforts of workmen A, B and C, but their resultant; this will be less if there is imperfect co-operation, as is likely in a shop where the system of management, however good in theory, is resented by the men. The main essentials of success are co-operation, cheerfulness, and the elimination of the irresponsible grumbler, but these are not attained by the Taylor system exclusively. Such systems are often resented by the men because they feel that overhead charges are thereby largely increased; men have told me that, while their wages are reckoned in tenths of a penny, it cost 2s. 6d. to get a split pin out of the stores, and they resent it. They do not resent a system which presents them with the material, drawings, and clear instructions for the work; they appreciate that. I think we ought to remember, in considering these problems, that a great manufacturing business is almost always started by one workman getting together a few friends who are efficient workers; under such conditions the output is large as compared with the input. If the business grows slowly, inefficient newcomers are weeded out almost automatically, but rapid expansion entails the employment of less efficient workers, and trouble begins. The teachers and employing class are responsible for the poor education of the bulk of the workers, and the small interest in their work which is the consequence; to my mind industrial fatigue is a smaller factor than industrial boredom. We need, in this country, and as our chief national asset, a host of men with initiative, craft skill and the experience to enable them to tackle their jobs with confidence. I doubt if we ought to engage principally in repetition work which could be done by aliens or by female labour, under such a system as advocated by the author; if we can supply the world with "Rolls-Royces" and keep our people fully employed, why make "Fords" instead? In our search for palliatives for the present, not unnatural, unrest strange schemes are mooted, such, for example, as welfare work. Part of it is a weird revival of feudalism, involving unwarrantable interference with the liberty of the worker; another part comprises the obvious duty of any decent-minded employer as regards shop conditions, and the rest is a piffling form of charity or pauperization. Self-respecting men do not want two-pennyworth of cake for a penny, or to have their canteen run at a loss to the firm; they prefer to receive adequate wages to enable them to pay for what they need. These matters should be considered more from the workman's point of view. Any good workman can get a good job to-day, and I do not believe there has

been a better time for the last 30 years for a good employer to retain, by proper treatment, good and loyal workmen. To my mind the enforcement of the Taylor system of payment at present would be a mistake, and would sacrifice the simplicity of time wages paid by the week for the complication of time wages paid on the stop-watch plan; it is preferable to keep an open mind for the reception of methods of paying wages on a juster basis. At the same time I appreciate the work done in the academic study of simple movements and machine operations, which may prove useful in the shops in another generation or two.

Mr. C. H. Stavenhagen: I should like to say a few words from the standpoint of organized labour. I am aware that the trade-union movement—at any rate the Electrical Trade Union—is not regarded, so far as its policy is concerned, with very great favour either by the contracting side or by the technical side of the industry, and I feel to a certain extent hampered by that feeling, which must necessarily exist here to-night. The author has discussed the problem, which is more or less circumscribed, of the necessity of workshop production. He has mentioned the relations of capital to labour, and so on. Some have thought that this matter should not come before the Institution, because it was semi-political in character. I think that most things are political if one traces them to their logical finality. It will be found that everything finally has some definite relation with the political side of life. I made it my business to study the industrial history of this country and I have asked myself—and labour men generally ask themselves—how it is that 500 years ago, according to Professor Thorold Rogers, there was an 8-hour day in this country, whereas now, or at all events prior to the war, it was not correct to say that there was an 8-hour day? We also ask ourselves how it is that very few workmen are able to continue in an even moderate prosperity during the whole of their working life. Labour also knows that, in order to get themselves into power, the two political parties have time after time promised certain reforms to the large mass of the people, but no sooner have they got into power than they have deliberately broken their pledges. Anybody who cares to study the question can ascertain for himself that my statements are correct. The working class have therefore every reason to suspect the promises of every political party which is trying to get into power, and it has very grave grounds for questioning the veracity of the pledges which are given. I can give one or two instances to show that these things appear very important to us and undoubtedly determine our action towards the other class—if I may speak of two classes. That division may not appeal to members. During the Napoleonic Wars from 1790 to 1815 something like 2,000 Enclosure Acts were passed by the Tory and Liberal parties. The result was that the landed people said they would pay certain taxes for the upkeep of land, lights, roads, etc. As soon as these Acts were passed, and while the people's attention was engaged on the wars, the Government passed another set of Acts called the Incorporation Acts, the result of which was to thrust the taxes necessary for the upkeep of these things back upon the working class community, but the communal land which had been enclosed was not returned. That sort of thing went on right up to the middle of the nineteenth century. In modern times we find that great bodies of capitalists have not been particularly anxious to consider the question of the division of wealth, so far as regards the improvement of the condition of labour generally. They apparently felt it was more important to increase the profits. These are movements which appeal to us as making it inevitable that a new system of society should come into operation. Looking upon this question from the point of view of production, one speaker suggested that the working class fear that if they accept the payment-by-result system it would throw them more rapidly out of employment. That is precisely what we do think, and we have heard no new economic proposition which suggests that this can be avoided.

Mr. J. G. Pearce: Some of the devices introduced by Dr. Taylor for increasing output have been utilized by unenlightened employers without recognizing that science must be introduced into industry so that it is beneficial to the human element rather than detrimental. The very object of its introduction, to increase efficiency and production, is defeated if the human aspect is overlooked. Very much more can be obtained from industries by the fullest co-operation of all grades of workers than by introducing an elaborate system of management which alienates the rank and file and which handicaps itself by heavy overhead charges. The conspicuous failure of Scientific Management to secure adherents does not arise from the lack of validity of the principles adumbrated by Taylor—although they are not in many cases strictly scientific—but from their dogmatic application to all kinds of plants irrespective of local conditions. Management is an art, however much the methods of observation, experiment and logical argument commonly used in science may be applied to it, and its successful practice demands not only academic study of principles and suitable personal qualities, but experience in practical application. The error commonly made in the tacit assumptions of the efficiency experts is that of supposing that an organization can be created and carried on independently of the personality of its director, i.e. that the man is determined by the job. As a matter of fact, the reverse is invariably the case, the job being determined by the man, and the organization takes shape and grows from his individuality. It is the recognition of these considerations which causes the British manager to take up an apparently conservative attitude to Scientific Management, for he does not mistake an organization chart for an organization, or a diploma in industrial administration for a qualification in management. It may therefore be asserted that the more extravagant claims of the Taylor group, which tend to reduce management to a code of rules that can be mechanically applied, have done much to encourage quackery, to hamper the development, inevitable in the long run, of the principles of organization, and to delay the recognition of a technique of management irrespective of the technology of the industry managed. Everyone will agree with the author when he says that no radical change in a

system of management should be made without the knowledge and consent of the workers themselves. This presupposes the establishment of confidence between employers and workers. Then better education, especially in the principles of industrial economics and in manipulative skill, and which develops general intelligence and understanding, is imperative. This will permit a deliberate compromise to be made between those who disagree profoundly with new methods as stultifying the mind and as causing monotony, and those who think that detailed time and motion studies are essential, for such education would permit workers to do several specialized jobs equally well, and to determine for themselves the most efficient methods of working. Change from one job to another may be largely determined by the exigencies of production. This may permit a deliberate compromise between the views of those who consider Scientific Management dehumanizing and of those who consider time and motion studies essential to increased output. Industrial concerns working under these conditions would be more stable and the organization would be elastic. Another factor frequently overlooked in connection with management is industrial research, which is vital to all growing firms. In the rare well-authenticated cases in which Scientific Management has made an improvement in a factory, we do not know how much improvement is due to better organization and how much to better materials such as high-speed steel. Industrial research represents a systematized progressive tendency and is a necessary adjunct where standardization is carried out. Scientific Management in Great Britain must therefore rest on improved organization, education, and research, and must comprise the study and practice of all factors which aid manufacturing efficiency and eliminate waste. It is more than probable that the demand for improved management will come from the labour side, provided adequate safeguards are set up, and engineers must therefore be ready to meet it.

Mr. J. R. Dick: I do not propose to discuss the first section of the paper, as there is not much debatable ground in it for those who have followed the subject of Taylor's system during the last 20 years, but I should like to give a few moments' consideration to the sociological side suggested by the alternative title. I assume of course that members of this scientific Institution are, like myself, quite satisfied with the results derived from the experiments in mechanics, physiology and psychology, which Taylor and his followers have made and which are set out in the paper. We must then examine the obstacles that prevent the ready adoption of the system in this country on a substantial scale. In the first place, I should mention the attitude of the employer himself, more particularly the present-day employer. He is living in a very fantastic age of topsy-turvy finance. His chief difficulty is what he euphemistically terms his "current price," which is of so elastic a nature that it covers all kinds of sins besides inefficiency of labour. He is therefore not in a mood to enthuse over the advent of Taylor's system on any large scale. The next obstacle is more serious—possibly the crux of the whole situation—namely, the attitude of the trade unions, or rather their authoritative executives. I have found from personal experience that the trade-union executive official is obsessed with the idea of what he calls a "normal workman," or trade unionist, just as the older economists used to postulate an "economic man," or one who would react always in a perfect manner to all the known laws of economics. This normal trade-union workman is thus defined:—"He is absolutely good at his work, capable and conscientious." But unfortunately, that being the original qualification for admission to the union, it is forgotten and the doors are opened much wider, and later one finds an influx of men of quite different qualifications. Then the union executive official reverses the definition, and we find that a man who is in the union, by whatever door he has managed to get in, becomes a good, capable and conscientious workman. We must not, however, hurl reproaches at the union authorities. I would much rather regard their position with a little intelligent sympathy, as their social democratic ideal cannot readily tolerate any very great differentiation between the respective workmen, either in the matter of ability, power of production, or wages. We must remember that the executive is a democratic body and is elected by the members as a whole, so it would never do for them to make invidious distinctions in the relative capacity or in the wages payments of the individuals on their electorate. There is possibly more in their argument than would appear at first sight, as regards the uniformity of the trade-union workman. As one of the leaders of a union said to me the other day, "Of course we admit that many of our men may be of an inferior grade, but there are others, and we take it that these men will be altruistic enough to give of their best, and their surplus output will compensate for the shortage of their less efficient brethren." As regards the man himself, he is at present in the happy position of having apparently a very reasonable sum of money in his pocket owing to the inflated currency, and he is not at all ready to be stimulated by Taylor's system of Scientific Management towards higher production and consequently higher wages. For good or bad he accepts the position, as it is, as fairly satisfactory. If we take then the composite attitude of the unions and workmen we find that they are not so much opposed to higher production as practically indifferent to it; in other words, they hope that the industrial world will manage to run on the lines of the Caucus race in "Alice in Wonderland," where everyone can run and all get prizes, without particular responsibility on anyone to provide the prize fund. The remedy is to educate and convince our real masters, the trade unions. In time they will surely recognize that a man's bodily presence in the shop is not equivalent to work done. The best procedure would be to apply first the scientific motion study on Taylor's system, and when it was recognized that a fair day's work done in the right way could be accurately measured, there would be a withdrawal of the union opposition to payment by results, which is the essential counterpart completing Taylor's system.

Sir George Gibb: The author has genuine zeal

for his cause. He takes a large view of our needs, and of the questions which must be considered in view of the future industrial requirements of the nation. There are stupendous difficulties in front of us, more grave, I think, than most people yet realize, but along the lines of Scientific Management we can see good ground for hope. The author says that we should study the principles of the system. The principles of what is called Scientific Management aim at analysis of the performance of work so as to get the best results in output and reduction of effort. There is much prejudice against Scientific Management. The obstacles in the way of its extension arise chiefly from prejudice. Everybody agrees now that our aim must be the maximum production of wealth. We cannot improve the standard of living unless we increase wealth, and we cannot begin to improve the standard until wealth has first been increased. All methods which will reduce the effort of labour, and get maximum production with least effort and least expenditure of time, are an advance on the road to the improvement of the standard of living. Payment by results must be extended. There is no other way of getting increased output. It is a great mistake in matters of this sort to be frightened at the working man. Prejudice can only be removed by reason and enlightenment. Workmen should be met not with arguments only, but with arguments and facts. The English people must abandon their habits of secrecy and approach workmen with sound arguments and with all facts and figures necessary to prove the case. If that is done, I confess I am quite satisfied that a good case for Scientific Management can be established and that the approval of the working classes generally will in time be obtained for it—when they understand that it means improvement of the standard of living by an increase of production with a decrease of effort and time spent on work.

Major E. A. Pells: I think there is one point which most of the speakers as yet have missed, and that is whether we shall be able to compete in the world's markets. I think that is the biggest problem we have to face at the present day, and one of the principal reasons why Scientific Management should be adopted in this country. After all, Scientific Management or any system of efficient organization is simply the outcome of analytical reasoning, which is something electrical engineers know a good deal about, because if one looks back through the past decade one will find that the progress in the electrical world is practically due to the fact that electrical engineers have possessed that faculty. I think that unless the manufacturers in all industries in this country take up some system of Scientific Management we shall be lagging steadily behind the rest of the world in competing in the world's markets. I was very interested to hear Mr. Paul give his opinion, because it brings us back to the old days when the master knew all his men and the men knew their master and were friends. Now with big companies and gigantic undertakings, which must come into this country, things are different. While on that question I think I had better say that some people seem to confuse mass production with Scientific Management. They are not the same thing at all. Scientific Management can be applied to any kind of work which is done by human beings. With regard to the paper, there was no mention of costing. Of course it is obvious to everyone—perhaps it is a detail—that Scientific Management without a good system of costing would be rather missing its point. There is another thing, I think, with regard to this question of the analysing of industrial effort and the application of the results obtained, and that is that there are rather two sides to it, namely, the side of research or study, and the side of application. I think there is a danger of confusing the two and thus confusing the issue, especially when putting the matter before manufacturers and employers of labour. They say: "We do not want experiments, and perhaps expensive experiments, carried out in our works." Another point is that the author said he would like to see some Committee or Council which would carry out the research work, which would work downwards through the whole of the industries of the country, and which would finally link up with some international scheme and so carry the method into working throughout the world. I think that is a mistake. Taylor had the same vision, but Taylor's idea was more to build up from the bottom and not build down from the top. One point seems to rankle in everybody's mind, namely, the suspicion of the worker, but he gets the best out of it every time. The employers too will get their reward in better and more settled social conditions in the country, and therefore will be able to go forward with their manufacturing projects and prove themselves successful competitors in the world's markets.

Mr. P. G. Pettifor: In addition to the reasons mentioned by the author, the term "Scientific Management" is objected to by many because it implies, by inference, that factories not run under the Taylor system have a non-scientific management. It should be remembered that the term originated in the States, where manufacture is more highly specialized than over here, and one factory may produce only one class of machine, and in many cases only one size of that class. Such conditions are highly favourable for the development of the Taylor system. Compare this with the conditions of the average machine shop in this country. They handle a great variety of work in comparatively small quantities, and the consequent short time a particular operation is in hand renders an investigation into the most economical method, and equitable piece rate, very difficult and in many cases impossible. In this respect, I do not quite agree with a previous speaker, who stated that mass production had nothing to do with Scientific Management. It seems to me that until our manufacturers adopt methods of specialization and mass production to a much greater extent than has hitherto been done, the full benefits of Scientific Management cannot be secured. The author suggests that factories situated in the country districts should pay the difference in labour rates to a common fund. One of the handicaps to factories in the country is that labour of the right class is frequently difficult to obtain, especially in the electrical industry, and to neutralize the advantage of the lower country rate would, it seems to me, tend to cause the owners of

factories to allow them to remain in, or be built round congested areas where labour is more easily obtainable. This, of course, is against the best public interest.

Mr. A. Vines: The author has used the title "Scientific Management" for his paper, but I cannot find that he has given therein any definition of what he means. The present habit of using words without defining their meaning causes very great confusion and trouble to manufacturers. Such words as skilled and unskilled men, dilutee, foreman, charge-hand, rate, seem to have a different meaning in each factory. Surely the words "Scientific Management" should convey much more than mere "motion study," and I would suggest the following definition: "Scientific Management is a system by which scientific methods of observation and analysis are applied to every process, operation, or movement which is carried on or takes place in a factory, with the ultimate object of eliminating all waste of energy, material and ability, providing the best working conditions and producing perfect machines." Accepting this definition I do not think there is a single works in Great Britain where the efficiency cannot be, and in fact is being, greatly improved by the application of Scientific Management. It depends, however, very much on the nature of the work carried on how far these principles can be economically applied. There is hardly any limit in a factory making very large numbers of one type of machine, but where the type is constantly changing and few of each type are made, details must necessarily be left to the individual foreman and cannot be planned beforehand to the same extent. There is one very real difficulty alluded to by the author, namely, the lack of practical scientifically-trained rate fixers, and if some institution could be formed where men could be sent and trained specially for the work it would be a great boon to manufacturers. Under the section headed "Payment by Result" we find the following statement: "The geographical situation of an engineering works should not affect the labour cost to the employer as this . . . gives an unfair advantage." The lower wages paid in the country do not necessarily mean lower cost of production, and it is quite as unsound to tax a company paying low wages in the country as to tax one paying a low rate for power in a town. I agree with the author that no serious opposition will be experienced from employees to the introduction of Scientific Management, but the employers must use common sense when introducing it.

Mr. C. T. S. Arnett (*communicated*): The method of management outlined by the author would be very difficult to work in the electrical department of a large steel works where a great variety of work is done, though I think it could be worked if one could get the right kind of man to create a number of standards for the different classes of work. The creating of these standards by which the different recurring jobs could be gauged would be a difficulty. In many steel works, however, the actual arrangement of the engineering management is far from efficient or in proper order, and this should be corrected before any detail work, such as that outlined in the paper, is carried out. At present, the general arrangement is that the mechanical engineer is the chief engineer, and chief adviser to the general manager on all plant installations and upkeep; and the electrical department chief is very often only consulted in a secondary manner, sometimes not at all. This, in many cases that I know of, has led to the expenditure of many thousands of pounds in subsequent upkeep due to the wrong type of machinery being installed. The arrangement that will give true progress and greatest output is to have an electrical-mechanical man at the head of an iron and steel works engineering staff, with one electrical-mechanical engineer as assistant, one electrical engineer in charge of the electrical department, and one mechanical engineer in charge of the mechanical department; for, as the author says, the first important point is to understand exactly what is taking place. This applies generally as well as in detail, and to understand how to manage properly a large engineering staff of an iron and steel works whose mills and blast furnaces are fully equipped with electric drives to the extent of a power-house load of, say, 7,000 to 8,000 kw., the chief and his assistant must be trained electrically as well as mechanically and must be men of good practical and theoretical training. Only by such arrangement of management will our iron and steel works maintain superiority over those of other countries, and only will the application of electrical engineering to such works reach its greatest efficiency or any efficiency at all.

Mr. J. E. Grant (*communicated*): The author is certainly right when he says that Scientific Management is an attitude of mind. Those of us who have learnt from experience know that men may be led successfully, but cannot be driven. If this is common sense, and "its function is to accept all that is good for humanity," then Scientific Management is a redundancy, a strenuous waste of nervous energy. I really doubt if the author can escape from the conclusion that, after all, science is applied common sense; that real Scientific Management is not opposed to common sense. Then why not be scientific, and ask ourselves what we mean when we loosely (that is unscientifically) talk of "a square deal between Capital and Labour," of a solution of the Capital and Labour Problem? With a more scientific definition of terms, we may find a correct solution—without knowing what we are talking about, any solution is out of the question. Is it not our own fault that Mr. Stavenhagen classified us as leisured, since we are so slow to claim the honour of being labourers? Let us apply common sense and cease talking of labour as though it were a thing apart. All the tragedies of history can be attributed to loose terminology—to the effacement of words and their meanings. There is danger in classifying as "non-producers" such indispensable labourers as pattern makers, millwrights, toolmakers, clerks, draughtsmen, foremen, salesmen, travellers, managers and directors. An impression has gained ground that wages are earned, but that salaries and profits are not. It is not realized that, properly speaking, all fall into the category of wages, or we should not talk of reducing wages in order to reduce the cost of production to meet foreign competition. How can there be prosperity in any country if the bulk of the population have small purchasing

power? When purchasing power gets into few hands, then naturally demand is small, however large unsatisfied demand may be. The reason why we have carelessly allowed ourselves to believe that profits and salaries are not earned, is that we have included in the term profits, gains which are not profits. All these burdens are supported upon the backs of labourers producing useful wealth, and now the last straw appears in the Taylor system of Scientific Management in the shape of a new horde of loafers with stop-watches in the workshops and elsewhere to see that the last erg is squeezed out of a few fellow-labourers. It is time to get our applied science into conformity with common sense. The menace to society is not in the working man, but in the loafer, and especially the expert loafer. Where compulsion is, there is no Scientific Management, only scientific slavery with a niggardly measuring out of a minimum incentive to endeavour. The correct attitude of mind brings about maximum wages, salaries, and profits for every labourer. It is in being impelled instead of being compelled that the true solution of the so-called Capital and Labour Problem is to be found. Our vain attempts, to solve the problem without first putting civilization upon a just basis, are very like the futile actions of the occupants of a house, the foundation of which has given way; and so they try to correct the slope by putting the pictures straight upon the walls, and by tying the furniture up to prevent it sliding along the floor. It is no use fighting each other inside the house because they find themselves overcrowded against one side of the building. Violent struggles may bring the fabric down to engulf them in ruin.

Mr. W. F. Keith (*communicated*): The scheme suggests a means of increasing profits by training workmen to avoid waste of time, thereby increasing production. The *quid pro quo* offered to the workman is "higher wages" and "shorter hours." That the scheme would increase profits and production is undeniable, but, in America, where similar schemes have been tried, rumour has it that the production of lunatics and nervous breakdown cases also increased and that workmen became "too old at 40." Taking a long view, the author's scheme is not unlike a proposal to nullify the insidious "ca' canny" policy by linking up and transforming into high-tension energy the various "bonus systems" that are being experimented with throughout the country. Administration would be by national and local boards with medical advisory committees, which would bring workshop control within a single step of nationalization. With regard to "higher wages," the trade unions appear to consider that the greater part of invested capital is, or originally was, unpaid wages. They maintain that, although mechanical labour-saving devices have increased production one-thousandfold, the workman is still only paid the equivalent of the cost of living and propagation. They believe that higher wages under this, the universal Iron Law of Wages, is merely an optical illusion, because, they say, if prices advance with money wages, real wages do not rise, and that real wages may be falling as they were during the period 1900–1911 when money wages were almost stationary while prices advanced about 10 per cent and profits increased. Further, they say that, though paid only a living wage, they must contribute to an unemployment fund for the purpose of maintaining workmen who are temporarily not required—possibly through the speeding-up of production. Perhaps this is one of the causes of the "ca' canny" policy; and if, as promised, the Government place an Unemployment Insurance scheme on the Statute Book, it may effectively stop the "ca' canny" methods and incidentally render the author's scheme unnecessary. Shorter hours, on the other hand, are due to labour-saving devices increasing production, and mean raising the standard of living. Unless evolution is held up in a cul-de-sac, shorter hours may arrive without labour making the sacrifices proposed by the author. Britain, we are told, is now a poor country, and had the country not been in an unsettled state the recent concession—the 48 hours week—by capital to labour would unlikely have been granted. The trade unions say, in this connection, that, as the hours of labour are reduced, the standard of living will rise and production fall until the idle class is forced by the economic law to do its share of productive labour. These contentions join issue with those of the author and I am of the opinion that he has not proved his case, as the mere suggestion that "hewers of wood and drawers of water" should do more work is tantamount to a confession of ineptitude on the part of those whose function it is to hasten the triumph of mind over matter by reducing, if not practically eliminating, manual labour by harnessing the known forces of Nature to serve the needs of mankind.

Mr. D. Martin (*communicated*): The author makes rather a bold assertion when he claims what he does in his title. "Scientific Management" as a phrase is catching, but when all is said and done it is just a phrase. In this country, ever since the introduction of machinery, the aim of the engineer (to take only one industry) has been efficiency, whether it be in manufacturing processes or otherwise. One has only to observe the progress made in the last 40 years in the reduction of the amount of coal used per unit of electricity generated, for a typical example. At its best, efficiency is only an aim towards an ideal condition of affairs, and the progress made towards that ideal is only limited by the progress of human knowledge, which, in turn, largely depends on scientific research. So far as it relates to shop management, it is quite a relative term, and to call it by a high-sounding name such as "Scientific Management" is misleading. In any case "Scientific Management" is conducive of suspicion in the minds of the workers. To make the claim that it is the cure for all ills in production is equally erroneous. To endeavour to force the system as it is known in America upon British industry is simply to court disaster. The author makes the astounding assertion that Taylor was the inventor of something new in efficient methods. Surely he must be aware of the enormous strides in efficient production made by British firms before Mr. Taylor was born. I would name only one or two such as Napier & Elder and Thomson of the Clyde shipbuilding industry, the Carron Company, the B.S.A. Company, Messrs. Tangye, Messrs. Guest, Keen & Nettlefold, the late Sir Joseph

Whitworth, and numerous others. For the successful operation of what the author terms the Taylor system two essential factors are necessary: first an unlimited supply of labour, and secondly unorganized labour. As a British manufacturer the author must know these two essentials are absent from the British labour market of to-day. I have been intimately concerned in works management since 1893, and during the war was one of the State's chief investigation officials into industrial disputes. So that, neglecting the short period during which I was on active service in 1914 and 1915, I can claim some 23 years' experience in a position covered by the phrase much used during the war, "the friendly neutral." As in many other walks of life, the looker-on always sees the most of a show. It was so in my case, particularly during the war. I am no longer an official, and I think I am not infringing the "Official Secrets Act" in anything I say here. The outstanding bugbears of industrial life are mainly four in number, and are: (1) The implacable and dogmatic employer; (2) the irreconcilable or agitator type of trade-union official; (3) the bureaucrat, and (4) the impractical theorist. Fortunately for this country neither of the foregoing have the final settlement of a dispute wholly in their own hands. In this respect Britain is at least years ahead of the practice observed in any other country, not excluding America. I fear the author is more of a theorist than any other. In saying so, I am led to that conviction (in spite of the camouflage in his conclusions) by the absence in the paper of remedies for alleviating the weaknesses of the Taylor system as it would apply to Britain. These weaknesses are many and I put them in the form of questions:—

(1) How would he eliminate the tendency to drive, the main weakness in all payment-by-results systems?
(2) How would he get over the tendency to monotony in the subdivisions of work entailed by scientific methods in a modern British factory which must be kept running between certain fixed periods of time?
(3) What are the compensatory advantages likely to be, arising out of the destruction of individual initiative in the large majority of the workpeople engaged in specialized operations, advocated by the Taylor system?
(4) Where is he likely to get, and who is to decide, the type of heavy labourer (essential to industry) in the ideal state of affairs pictured under the Taylor system?
(5) Is it not a fact Taylor had no experience of trade unionism as it is understood in this country?
(6) What would the author do, assuming all labour was union labour, as it is in the majority of trades in this country, in the event of his shop becoming blacklisted? It may be due to a demarcation trouble or it may be due to the employer's refusal to discharge a foreman or a charge-hand giving a perfectly legitimate instruction, which may be, as not infrequently happens, obnoxious to members of a certain trade union. These are two common disputes.
(7) How does he propose to get over the difficulty of a trade union rule (the A.S.E. for example) prohibiting members, under a penalty, undertaking piecework or other system of payment by results without the knowledge and consent of their district committees?
(8) Having the ideal in mind as outlined in the closing sentences of his paper, to wit, to treat all men on the level so far as earnings are concerned, how does he propose to differentiate between the earnings or the rates of wages payable to the skilled, semi-skilled, and unskilled?
(9) Without Government control or its worst form, bureaucracy or strikes, who is finally to decide the district rates in the event of the district Whitley Committees failing to arrive at agreement?
(10) How are prices to be altered in the event of an improvement in the method of production, for example, taking place? Progress in this connection is never stationary.

These and a hundred other cognate questions come to mind, but I look in vain in the paper for a solution. In conclusion I would remind the author that while we owe America much in the way of improvements in many things displaying inventive genius, much of it is due to latent inventive genius imported into the country, enticed it may be by the greater scope to be found in a younger country, unfettered with restrictive trade-union rights, customs and privileges. It is essentially a country where the idea of the survival of the fittest has full play, though that idea is deprecated by the author. Britain, when all is said and done, has little to learn from abroad in the handling of the labour problem in industry. In 1802 the first British Factory Act was passed dealing with conditions, ventilation, etc., and is an example of pioneer efforts in this connection; while another pioneer effort is the enunciation in 1919 of practicable international labour laws for the first time in history by the Labour member of the British Cabinet, under what is known as the Labour Charter of the League of Nations. That Charter, in my opinion, is a move in the right direction. In essence it is an attempt to standardize labour conditions of other countries up to the British standard. If it succeeds and becomes acceptable it will tend to alleviate the pre-war international cut-throat competition, incidentally one of the causes of the war. What hope has Britain in a world trade if she, by observing fair or reasonable conditions in her industrial life, handicaps herself to the tune of being 100 per cent or more dearer than her American or Japanese Allies for example? What has been done in Britain cannot very well be undone now, so it would appear to be the better proposition, I think, if we exerted all our influences towards a more uniform international standard, based on the lines of the British minimum. Having obtained that desirable end we compete fairly and without the present handicap. At least that is likely to be one of the many remedies towards a more contented industrial life in Britain.

Mr. O. L. Record (*communicated*): I read the

paper with all the more interest owing to the fact that a few years ago I had the pleasure of visiting a factory, the manager of which had occupied himself with motion and time study (whether he was acquainted with Dr. Taylor's work or not I do not know) and had applied the results in the shops. It was extremely pleasing to see the superior skill, efficiency and speed with which the various operations were performed. I think the author is wrong in giving to the Taylor system, i.e. to a particular system or method, the general term "Scientific Management" without any qualification whatsoever, as if it embraced the entire field and every possible development of the subject. In this he is only following American engineers, but I consider some of the earlier terms applied to the Taylor system to be very much more suitable and less egotistical.

Mr. I. V. Robinson (*communicated*): Many of the speakers have taken exception to the name "Scientific Management" and complain that no definition has been given. I think that reference to Webster's Dictionary will give a complete but brief definition: "judicious use of systematic knowledge to accomplish an end." This definition is sufficiently wide to allow of the application of Scientific Management to the whole domain of human activities, which is suggested in the paper. As one who has had a little experience in the attempt to introduce the initial stages of Scientific Management into large works, more particularly with regard to time study for the logical fixing of basis times, bonus rates, etc., I should like to refer briefly to the attitude of the machine operator towards time study in particular. I was quite frank and told the operator that I proposed to time him, and that my reason was to ascertain whether it would not be possible for him to earn more money by getting a greater output. I used a special timing book, originally introduced by Mr. Sanford E. Thompson, one of Dr. Taylor's earlier assistants, in which the watch is not displayed ostentatiously before the operator. I have stood beside machines for hours at a time and noted the intervals taken for detailed elements of the complete operation, and I do not think the operator fully appreciated the vast amount of information which this method of observation enabled me to collect. In no case was any objection made by the operator to this method of timing. Such time study enabled me to collect at least the beginning of a set of data relating to the machines under examination which would be of very considerable use, not only to the works in which the data was collected, but to all works where that particular machine is used. It should be the duty of the machine-tool manufacturer to supply such data with his machine, assuming standard conditions (which would require defining). Very few machine-tool makers appear to have tackled the proposition on these lines. Some of them are prepared to give a guarantee as to the number of pieces turned out per hour and to send a demonstrator to show that this can be done. This form of guarantee, while being better than no information at all, is not so satisfactory, as it does not enable the purchaser of the tool to determine accurately the time that will be occupied in the machining or turning of any article beyond those submitted to the maker. If the machine-tool makers issued such a book of standard unit times for their machines, users would then be in a position to calculate their own basis times logically and accurately. The compilation of such a book, if not undertaken by each machine-tool maker individually, could surely be undertaken by an association representing the interests of the machine-tool makers. If they do not rise to the needs of the occasion, then some other association representing engineers should tackle the subject and prepare for their members such a book as I have indicated. The paper contains a paragraph headed "Scientific Management versus Common Sense." In spite of the first sentence in that paragraph, I consider Scientific Management to be applied common sense. It is no discovery due to Dr. Taylor, but to Dr. Taylor we do owe the clear enunciation of the best method of ascertaining the quickest and most economical way of accomplishing any end, the word "economical" being interpreted in its fullest and most complete sense. Another point referred to in the discussion is the confusion which exists in the minds of many people as to the suitability of Scientific Management for shops not engaged in the mass production of any article. Scientific Management can be applied to general engineering shops and certainly to shops producing such articles as, say, marine engines, where the type is fairly constant but the number per annum comparatively small. In such works, the planning department is capable of rendering very effective services and can allow the management to know exactly whether any particular engine is up to its scheduled time and, if not, what delay there will be in completion. With a properly designed progress indicating-board, it would be possible to point exactly to the one forging or casting which is behind its schedule, thus holding up the date of completion. The author refers to one point of very great importance, as to the need of considering another party other than capital and labour, i.e. the consumer. The only effective way of reducing prices is to produce more goods, and Scientific Management will enable this to be done. As goods are only paid for by goods, those who produce more will be in a position to purchase more. In order that the increased output should enable lower prices to be charged, it is essential that some form of payment be adopted other than a flat piece-rate. With a flat piece-rate, the cost per unit produced is only reduced with an increased output by the saving resulting from the division of the standing charges over the increased output. This is not sufficient to reduce the prices considerably and so increase the possible market, and some reduction in the labour cost per unit must be obtained. This is a particular advantage of the Halsey, Weir or Rowan systems of premium bonus payments.

[The author's reply will be found on page 366.]

DISCUSSION BEFORE THE SCOTTISH CENTRE, AT GLASGOW, 9 DECEMBER, 1919.

Mr. J. H. Bunting: I do not quite agree with the author when he speaks about the immediate formation of National Boards, because I think we have got to do something ourselves before we can expect the Government to do very much for us. I see no reason whatever why the principles of Scientific Management should not be introduced into the factories of this country, not necessarily in the form in which they were put forward by Dr. Taylor, but, in some form, they might certainly be introduced in most cases with the greatest possible advantage. I have seen these principles at work in a modified form and with remarkable results, and I do not think that, if they are carefully introduced at the present time, we are likely to have serious trouble with the trade unions. I am in entire agreement with the author when he says it should be our policy to endeavour to educate the whole country on this question of Scientific Management, so that the workpeople, as well as the employers, will understand that we are not endeavouring to detract from their value, but to add to their usefulness. I am satisfied that the person who requires education on this subject is the employer rather than the workman, and I am convinced that, if those of us who are seriously thinking about this subject to-day, will look back four or five years and consider the point of view from which they would then have regarded a matter of this kind, they will be appalled at their own then mental attitude towards such a proposition. I feel that we have learned a little—but only a very little—and that we are just at the beginning of a very important and large subject and one which will be of great advantage to this country in the immediate future.

Mr. W. J. Morrison: I will confine my remarks to a few suggestions for the introduction of this system. I cannot help but feel that some of us, perhaps all of us, can take a lesson from what we have been doing. We were burning our boats hopelessly for the introduction of such a system, and a great deal of the responsibility of this lies at the door of the employers of to-day. Instead of suggesting a shorter working week as a step in the right direction, the worker had to fight for this; and then we have had all the loose talk by the employers since the introduction of the shorter working week about the effect of the increased cost in wages. In connection with this I wonder how many of us have studied the subject carefully enough to understand that if we are manufacturing an article and a workman makes in a day of 8 hours four of these articles for which he receives a piece-work price of 2s. 6d. each, then if we can get the same workman in the same time to produce six articles instead of four, we can afford to pay him 3s. 6d. per article instead of 2s. 6d., or in other words for a 50 per cent increase in production to pay a 100 per cent increase in wages. Before introducing a system like that outlined in the paper, we have to convince the workmen of the benefits they will receive and, in my opinion still more important, the benefits the employer will receive. We must educate ourselves first, because if higher wages have to be paid we must obviously have increased production, and this can only be done by cutting down to a fine point the matters over which the workman has no control. To enable us, as the author has pointed out, to get at the real facts this can only be done by recording on a scientific basis. Some of us already must have a good idea of the difficulty that lies before us in convincing the workmen, knowing as we do the difficulty that exists at present in attempting to convince them that by putting them on piece-work they are going to earn more money. We must also, as the author has indicated, educate the staff on the subject, and we can only, in my opinion, do that by first of all so convincing them that the principles on which we conduct our business are equitable. I am very enthusiastic about the matter and I think that if employers do not move in connection with the introduction of Scientific Management, it will only be a question of time before organized labour will step in and force our hands.

Mr. T. E. Herbert: There is nothing in the paper which I cannot subscribe to, and I have for long been convinced that Scientific Management is the panacea for most of our industrial ills. I certainly feel that, strongly as the author has put the humanity aspect of the subject, he has not put it strongly enough. I should have liked to have seen it brought out even more strongly that the whole basic idea of Scientific Management is the substitution of help and assistance by the functional foreman for the mere bullying and driving of the ordinary general foreman; that it is founded on ascertained facts; that its basis is truth, scientifically ascertained and analysed to detect error; and that it is designed to produce that ideal brotherhood of man which can alone dissipate the clouds of suspicion and distrust. The mere fact that encouragement and help take the place of vindictive criticism and punishment must necessarily improve the relations between capital and labour. It is of course true that Scientific Management detects and eliminates false effort and secures efficiency in avoiding waste in both materials and human energy, but its foundation is, I suggest, an alteration in the attitude of the employer to the employed. Much of our difficulty the author rightly ascribes to the sheer ignorance of the so-called business man, who often is neither an engineer nor an accountant. Such a man often fails to realize the sanctity of human life, and has not even discovered that to wear a man out is bad economics if only because it takes time and money to train his successor. Such a man often fails to realize the stupidity of reducing a piece rate once fixed. In the old days of small firms the link between capital and labour was much more human than it is to-day, and in my view Scientific Management will serve to restore it even in the largest organization.

Mr. A. Page: Any system which will increase efficiency and eliminate waste, in whatever form it may be found, is likely to meet with approval, always provided it is accompanied by the raising of the status of the worker. The first hurdle which has to be surmounted is referred to near the bottom of the first column on page 331, which reads "I do not see how Scientific Management can progress at all unless the unions are

included in its scheme." How are we to get rid of the suspicion of the unions which leads to so much friction and is the main cause of limitation of output? Until that is accomplished, any attempt at motion and time study would be futile. The gaining and retention of the goodwill of the worker is the essence of successful management. There is increasing evidence of a more sympathetic attitude on the part of the employing class, and there is promise in the activities of the Joint Industrial Councils. Dr. Taylor's work appears to have been very thorough, although it is difficult to grasp why he required to spend 26 years to find the answer to the questions at the top of page 332. The scientific handling of labour is the most difficult part of Dr. Taylor's system, and a great deal of spade work will require to be done before the British workman will agree to make an automaton of himself in return for the satisfaction of knowing that he has completed his job with the minimum of effort.

Major H. Richardson: I am tempted, in answer to the author's express requests for constructional criticism, to make one suggestion as to where this matter of Scientific Management could be pushed forward rapidly in this country. Many years ago it was necessary to make some long experiments on electric traction with a view to finding out the highest economical speeds, etc., and several German firms at that time found money by what was called, I believe, a "Study Club." My suggestion is that some of the leading firms in the British Electrical and Allied Manufacturers' Association do set the example and initiate progress on the lines suggested in the paper. Valuable and necessary as the principal work of the B.E.A.M.A. has been, the continuance of such work must nowadays be to a great extent a matter of routine, and there is surely room among its activities for the development and application of enlightened methods in workshops, etc. I should like to emphasize the increased value to this country of getting in first on such a scheme as this. A few days ago, in a discussion in another place on a matter affecting engineering, a speaker was dangerously optimistic, in my opinion, in certain boastful references about Britain having unlimited resources and that our prosperity, up to and during the war, was due to these resources. I refuted this, drawing attention to the fact that the prosperity of this country was not and is not due to its preponderance of resources, because these resources are a small percentage of the world's supplies. Our prosperity was due solely and only to the fact that we were the first to develop, and rapidly develop, what resources we had. I take the liberty of mentioning again this point of view to-night, because the importance of getting first in the field cannot be overestimated.

Mr. J. S. Nicholson: I merely wish to remind members that we have now got at the University of Glasgow, owing to the generosity of Mrs. Loudon of Johnstone, a Lectureship in Engineering Production.

Mr. J. Richardson: One aspect of the case for Scientific Management which cannot but impress anyone who listened to discussions on this subject prior to the war, is the difference between those early discussions and the tone of the remarks made this evening. Prior to 1914, so far as my knowledge and experience go, no paper was read on Scientific Management but was met by ridicule and scorn. At the present time advocates of almost the same system are most favourably received, and in the discussion all agree with the first principles as laid down—at least if they do not agree they have not the courage to say so. Those of us who advocate this system feel that in this country very little actual progress is being made towards its application in our workshops. That there is progress being made is undoubted, and perhaps even more than is appreciated, but more is required. The important lesson of the paper appears to me to be that within the next few years we are likely to be faced with a crisis or crises in our industrial affairs which can only, or can best, be met by adopting the principles of Scientific Management. How then can we start to put these principles into practice? In the paper it is suggested that a number of Joint Boards of employers and employed should be set up to arrive at a solution, and the reading and discussion of papers like this is undoubtedly a preparatory step to such a move. On the other hand, careful thought will reveal the fact that we have not got in our workshops to-day staff officers or young men who could put into operation the system of Scientific Management, supposing in the extreme case that it were made obligatory by means of Act of Parliament or some other similar course. We must look to the technical institutions and the universities to provide the staff officers for the future.

Mr. J. H. Huntley: I think we should note especially that the author has dealt with the broad principles of Scientific Management and not with any particular system. Many people think that the installation of a card index or other system is Scientific Management, whereas these systems are merely tools used in its application. The proposal for the introduction of national or international Industrial Boards is, I believe, original, but I think these Boards should have their origin in the workshop, for the reason that the setting up of a national board would be a difficult matter to commence with. It would be easier to begin in a small way and gradually extend the movement, district by district, until ultimately a central or national board was founded based on the experience already gained. Another point which a number of speakers have already mentioned is the comparative ignorance of employers on this subject, due probably to multiplicity of interests and lack of time for personal investigation. An amicable relationship between the employers and trade unions to discuss this and other matters will not, I think, be easily reached if the employers hand over their side entirely to the secretaries of their federations, who are usually lawyers knowing little of workshop practice, and who usually confuse matters and cause distrust by the use of unnecessary legal terms, the meaning of which is not clear to the average man.

Mr. L. M. Jockel: As a practical engineer I am interested in what I might call simple or elementary improvements in management, which hardly come under the title "Scientific Management," and I have seen their application in one or two of our large industrial concerns in England. Also in connection with the

training of apprentices in such works, I have been brought into touch with the actual value of even the elementary principles of science in management. I am convinced that Scientific Management will come: it is only a question of time. In the meantime, I think a great deal more could be done on what I might term the elemental side of Scientific Management. To give a few instances. I have seen one of the simplest ideas in ordinary factories in the shape of the suggestion box. Not the ordinary suggestion box, but something based upon that principle, as a link between the employees in general and the management or staff. It forms a very crude but, nevertheless, practical link of no small value between those two departments. I think a great deal might immediately be done on these lines. I believe too that a great deal could be done wherever we are manufacturing, by the adoption of even simple elementary reforms which lead to economy and improved results. I myself once tried the introduction of simple graphical methods, and the result upon the working was certainly beneficial. It undoubtedly had a good effect in this particular case, and was easily explained to the men. I think a great deal could be done in educational matters in the works itself. This would be specialized educational or technical knowledge, and would form a valuable link between parties and give beneficial results to both.

Mr. D. Keachie: The difficulty it seems to me will be in introducing a system on this principle, under the name of Scientific Management. There are many factories in the country largely run on scientific or practical lines, but they have not adopted the name Scientific Management" because of a certain amount of odium attached to it, possibly reflected from the cold-blooded manner in which it was introduced in America. There is one point in the introduction of anything where an increase of production is wanted, that is the method in which it is introduced. The spirit is almost all that matters, and if we have the proper spirit other things will follow. The old way—"There is a job, take it or leave it"—has got to be abolished, and we have to realize that workmen, like other classes, are human. If the men are treated in proper fashion, I have no doubt we shall get the results. This is not philanthropy, but a sound business proposition. Give the men our confidence, inform them of any new method of work to be introduced, make truth and straight-dealing the watchword, and the response will be such as to give us a return in trade which will probably surprise most of us. Another point—this may get over the bogy of shorter hours and bigger wages; we welcome them both. They can be amply offset if everyone goes thoroughly into the management of their own affairs. At this time it is good to put all our houses into order. It is not difficult to see in many of our factories to-day open doors of waste, which could easily be closed by the management adopting proper methods of control.

Mr. J. F. Nielson: The author has omitted to include in his list of authorities consulted the name of Naval Constructor T. G. Roberts, U.S. Navy. I would strongly recommend to those interested in shipyard management a paper read by him before the (American) Society of Naval Architects and Marine Engineers, 15th and 16th November, 1917, entitled "An Analysis of the Principles of Industrial Management."

Mr. W. G. Booker: One of the best forms the application of Scientific Management might take would, in my opinion, be among our apprentices. The boys of to-day are the men of to-morrow, and from these we shall reap some of our leaders of industry. Our present system of training for apprentices in most shops is bad. So far as I see the position, the first few months of the first-year apprentice are spent probably in store work, or other minor work such as messages between departments, etc. After this period he is considered to know something of the routine of the shops, and jobs on the tools are given him, with a few verbal instructions from his foreman, or the journeyman with whom he may be placed. These jobs he does according to his own initiative, and in most cases with no practical demonstration in the use of tools or material, and so the majority climb from one class of work to another throughout their apprenticeship. Here, surely, is where one seed of Scientific Management could be sown. The first teachings and impressions gained by the young are the most deeply rooted and lasting. Therefore, scientific training should be brought to bear on them from the first day they enter the works, viz. the correct handling of tools and material, the correct and most efficient method of doing a job, the correct cycle of operations, and the elimination of all unnecessary motion or handling. We should also adopt what is known as the instruction card, which should not only instruct the operator the method of doing such operation, but also state a known time in which the operation can be accomplished, this being predetermined under scientific principles; and it should embody, for each operation as a whole or singly according to the nature of the work being done, that very important point described by the author as the "fatigue factor." This in my opinion should not draw very great opposition from the practical trade unionist, for who could object to such a sound scheme of training the young the best way to go about their daily task. Is it not the duty of any trade union, apart from striving for better conditions of pay, etc., for the workers, to supply employers of labour with first-class tradesmen? Also, the employer training his employees under scientific principles will surely be creating a great asset for the British engineering industries.

Mr. J. B. Mavor (*communicated*): The problem of central control of scientific management strikes one, at first sight, as one which would lead to high general efficiency. But the complex nature of the task involved is such that, to my mind, would lead to unwieldiness, as in all other Government offices. Take, as one of the many examples, the standardization of a simple operation such as the boring of bushes. Would the sub-branches, as detailed by the author—say in a district like the Clyde—fix methods and times for a complete range of diameters, to be applied to the entire district? Would their duties comprise the fixing of suitable tolerances to comply with the standard of fit and finish required for every product of their district, and would they make special allowances for the composition of the different alloys to be cut? If so, records of all

motion, studies, equipment, records of plant available, and analysis of materials, would have to be carried in reference centres. These reference centres would have to cover the range of establishments in the district, from the ultra efficient down to the jobbing establishment. Further, is it quite clear that Scientific Management, as advocated by Dr. Taylor and his disciples, can be applied without the premises of standardization of product? If this is not so, it would appear that the road to be travelled before the above-mentioned central control can be achieved, is very long and very thorny. When the next economic depression comes, only the establishments bearing the hall-mark of some form of Scientific Management stand much chance of survival; but I fear I must differ from the author on this one point: "He travels fastest who travels alone," and all that can be hoped for, or that can be done at present, is to create a strong bias as to the ultimate destination.

Mr. A. Stubbs (*communicated*): There seems to have been a decided effort on the part of the author to generalize and to set forth "Scientific Management" as the panacea for the social problem of to-day. Whilst it would seem that there is more promise of success in this direction than in any of the alternative schemes before the public, one cannot but realize the speculative character of the paper. In considering the work of the Industrial Research Organization which is to establish standard times, etc., with local factors, it seems to me a wrong idea to neglect the local cost of living. The cost of living and the workman's general environment are very important considerations, and if no account is made in the wages bill there must be some alternative which I have failed to find in the paper. It is these factors which enable labour to determine indirectly where industry shall be established. These factors account for the immobility of labour, and industry must pay the price of transferring the same, a condition of affairs which it was necessary to recognize at a cost during the war when munition factories were being erected in all parts of the country. Whilst the consideration of detail would have reduced the scope of the paper, it is probable that the more immediate results will be obtained from such considerations. Production to the engineer is like a mathematical equation with all its various items expressed in the final product. A costing system is a means by which the items or terms of this complex equation may be solved separately. The result of such a system to the engineer is that he has a determinate equation in which every quantity is definite and its relation to the whole clearly understood. Without such a system he has an indeterminate equation the solutions of which at the best can only be guessed. Costing will be the basis of modern production and the means by which an increase may be obtained. It therefore behoves every engineer to understand and to be taught the elements of costing. It will be a particularly easy subject as he is already familiar with mathematical functions and their relation to one another. Just as the engineer may think mathematically without being a mathematician, so also he may think in terms of costs without being an accountant. There is a proper way, time and place to do everything, and each of these factors is important; their influence upon the final product must be understood. By the adoption of a proper mental attitude towards the problems of production it would be possible to effect enormous savings in our factories. We should not see, as we often do, many pieces of machinery assembled together passing round the shops as one piece to be worked upon in various places. It would be obvious that an unnecessary "oncost" charge was being incurred, viz. capital interest, factory floor-space, and excessive handling. It is important to note that these savings would be obtained without introducing elaborate and expensive accounts into the office. A costing system should serve to stimulate one's mind, and the accounts to confirm one's conclusions. When introducing "cost accounts" it is necessary to define beforehand the products or groups of products which are to be costed, the processes under which the articles of cost are to be collected, and the overhead charges which must be allocated to each process.

[The author's reply will be found on page 366.]

Discussion before the North-Western Centre, at Manchester, 16 December, 1919.

Mr. H. Mensforth: There are many things in connection with the paper, or opinions expressed in it, with which I do not agree. In the first place what we are out to discover is what is wrong with industry at the present time. It is not the lack of science. However willing one may be to adopt what science teaches us, that is not going to put our industry right. What has been lacking in the past has been humanity, and so far as I have read Dr. Taylor's writings on Scientific Management there is a lack of humanity throughout them all. He says that, up to now, man has been recognized as the first consideration, but that in the future man will have to take the second place and system will come first. Well I shall never agree to that. I say the human element must come before any system. Dr. Taylor further says that the principal object of Scientific Management is to produce the greatest prosperity for the employer and, parallel with him, of the employee. I say there is another thing that he should have included; it must be to the common good of the community. One of the historical examples of Scientific Management relates to the handling of pig iron. Dr. Taylor found that men working under ordinary conditions could handle 15 tons of pig iron per day from a dump on to a wagon. By training these men and getting them to work to a watch, as Dr. Taylor honestly said, treating them as you would an ox, he was able to get them to load something like 45 tons of pig iron a day. He says that he has eliminated waste, so far as this particular job is concerned. I agree with him that he did. But taking the community as a whole, did he eliminate waste by utilizing these men simply as beasts of burden and eliminating their intelligence? The whole idea at the

back of Dr. Taylor's mind in speaking of Scientific Management was to set up task work, and however successful he may have been in the States—and we have only to read the papers to realize the extent of that success, because the industrial conditions there are generally worse than in this country—I do not think Scientific Management can be established here on those lines. I agree with science being employed in management, but if we go away with the idea that such schemes as those described by the author can be adopted, I think we shall find we are wrong. They cannot be adopted with the present state of feeling among our people. They will not have that sort of thing. They will not have men who do all the brain-work for them, who leave nothing to their intelligence but expect them to move simply as they are told. The average Briton knows perfectly well that usually the shortest way between two points is a straight line, but when we order him and lay it down in writing for him that he must take that way he will not do it. In dealing with a works we have to tackle practical things. Imagine the works where the workmen are responsible to eight different men. There is one job I should not like in connection with those eight, and that is the job of the disciplinarian. It is hopeless to expect one man to take instructions from eight; it is not possible. With regard to the proposal to set up some national organization for making piece-rates or time-studies; any of us who have a knowledge of running shops must know that we cannot get a national system of time-studies; things vary so widely. The author says he would have local or district boards which would go over the figures put forward by the national organization, and then we are to have shop committees consisting of a combination of the trade-union representatives and of the management. I suggest that we have arrived at that stage to-day. We have cut out the other stages, and if we can get the proper atmosphere (which to my mind will not be got with slide rules or stop-watches) I believe we can obtain the output we need without stultifying the brains of the men who are working for us.

Mr. A. R. Stelling: It is just 9 years ago this week since the first contribution by an Englishman in England to the literature of Scientific Management was made. This was a paper which I read before this Institution. Since that date we have made much positive progress in this country. But with all due respect to the present author, I wish we had had another paper to follow up this policy. I think this paper ought not to be called "Scientific Management" but rather "Idealized Taylorism." It is more or less a repetition of facts which were published in America some years ago, and the author has given us no indication of what has been done in the past 12 years in this country in the way of Scientific Management. Since Dr. Taylor's views were brought to this country and studied by employers we have developed a British Scientific Management which aims at getting the maximum output from the factory, and this is a totally different thing from getting the maximum output from the individual. Throughout the paper we have had emphasis laid on the output of the individual, and we have had no indication of the pitfalls and difficulties which lie in the way of those who would apply Scientific Management in this country. I also regret to note that there is no mention of the excellent work done by Professor Kent of Manchester University, by Dr. Vernon Hill, Dr. Collis and other engineers. It is no surprise to British engineers to hear that a book has been written on the physiology of work; it had been known to them for some time. Dr. Kent's work is equally important and equally valuable and should have been mentioned. British Scientific Management recognizes that Taylor's four great principles are as true to-day as they were 30 years ago. Those principles are: (1) The study of the job; (2) the selection, training and development of the worker; (3) the hearty co-operation of the worker; (4) the adequate division of the responsibility. We start with the study of the human factors, the conditions which surround the worker and the management, and generally the conditions of the factory. We recognize that there are certain psychological lines which must be followed; also, that there are certain limitations in the question of fatigue. May I say in passing that I think every works manager worthy of the name ought to be the judge in his own factory whether the work is too strenuous for his men or not. He must have that ability just as an officer in the Army must be able to form a similar judgment in the case of his own men. He must know whether the men are working to the detriment of their health or to the best of their ability. If we leave it entirely to the medical men we shall not get very much further. When we have got our men in the right frame of mind and convinced them that we are seeking the elimination of waste, we can bring our machinery up to the mark and go for the minutes we have lost. That brings me to my definition of Scientific Management. It is the elimination of all forms of waste. Waste of management is the waste that follows from people rushing about doing things which it is not their business to do, instead of the whole thing being properly thought out and methodically arranged; waste of energy and vitality, men doing work for which they are not fitted or which is too hard for them; also waste of skill; there is a tremendous amount of skill wasted in our factories to-day, simply because we do not record the best skill and teach it to the men. Then there is the waste of time. Time is lost in moving work about the shop. We must overcome all these wastes, and British Scientific Management will overcome them by methods which are intensely human and directed by common sense. We start with investigation. We find out the why and the wherefore and get at the bottom of everything. Then we apply common sense and see whether the new system can be applied to our factory. Does it come within the limitations of our factory? Is it economical to do it? What is the use of working out a time card containing 40 elements for an operation on one article only which only takes three minutes to perform? That is not common sense. When we have got those things we want a square deal between the men on the one side and the employer on the other, perfect frankness and perfect agreement over what is going to be done. Those are the lines of British Scientific

Management. I have a chart which shows the application of these principles of Dr. Taylor to the various classes of waste, and the methods which we employ, and it will be found that they are all perfectly human and "common sense." The elements then are: investigation, common sense, and square dealing. A great deal of opposition has been based upon the failures of the past. People have tried to apply certain portions of Scientific Management piecemeal, without considering it as a whole, a unit composed of human and mechanical elements. They have practised timing with a stop-watch with the idea of limiting earnings. instead of trying to find out how easy the job could be made for the man, and the opposition has been very bitter. Scientific Management is not, as the author puts it, a solution of the problem of capital and labour. The solution is to be found in the coming together of capital and labour, and here Scientific Management with its ideals and its common sense will form a positive programme for progress. The sooner this programme is drawn up and agreed upon, the better will it be for all parties.

Mr. H. Allcock: We are evidently in general agreement that the British workman cannot be driven but must be handled with due regard to his temperament. Taylorism appears to be based on a kind of German regimentation to which we are all instinctively opposed, and I endorse Mr. Mensforth's views as to the danger of de-humanizing industry. It seems to me that the recommendations of the Higher Production Council are more in keeping with the British temperament because, in appealing to the team spirit, they are appealing to that which is already so highly developed in British sports. For the benefit of those who may not have noted the proposals of the Higher Production Council I would explain that they are based on a plan adopted by Messrs. Priestman Brothers of Hull who claim to have proved its success after two or three years' practical experience. In agreement with the workers the managers assessed what they called the standard output per month. The output of each month is compared with that basis and the pay is varied accordingly. For instance, assuming the standard output per month to be 100 tons and that this is exceeded by 20 per cent, raising the output to 120 tons, then the pay of everyone in the establishment from managing director to office boy is raised 20 per cent for the month immediately following that of the increased output. It is thus recognized that the first business of all employees is to facilitate output, and co-operation becomes the keynote of the whole establishment. I think it is very important that the extra payment should very promptly follow the extra effort, because the average working man does not appreciate any scheme put before him for his better pay unless he is due to receive it on Friday night and every Friday night. It is useless to propound a profit-sharing scheme under which he may be entitled to 5 or 10 per cent dividend at the end of the year—that is altogether too remote to attract him. In my opinion that aspect of the case deserves more attention than it has hitherto received. We must surely be all agreed that the only way to increase output—and output must be increased if we are to maintain the present high wages—is some method of payment by results and, I would again emphasize, the "payment" should follow the "result" as promptly as possible.

Mr. H. Pilling: I find myself in general agreement with the criticisms already expressed on this paper. The impression made on my mind when I read it was that it was an extremely hard paper. I can quite understand that in a factory where the system has been applied beneficial results might be obtained, but I can also understand that only workmen who are in receipt of a high wage would work in such a factory. I very much question whether any good is done to an industry by driving men to the utmost possible effort in an almost inhuman kind of way with the necessary result that very high wages have to be paid. In these days most people are agreed that capital and labour are equal partners after a certain point has been reached. Not much is said in the paper on the profit-sharing side of this question except that on page 335 there is a remark about the Federation of British Industries. It is stated that in one of their Reports these remarks occurred: "Profit-sharing is proved unsatisfactory when scientifically investigated, and it is therefore regrettable that more time should be lost travelling once again along this old cul-de-sac." I am not prepared to agree that profit-sharing is really unsatisfactory. It may be unsatisfactory as hitherto applied. My brother presented to Bolton Traders' Association in 1917 a report on the profit-sharing schemes of this country. Particulars were given of 299 schemes of which 163 had foundered, and at the time the report was presented 136 were still alive. Very few, however, were really satisfactory and the reason was clear, namely, fluctuating profits. Workmen, while quite willing to participate in rising profits, are not satisfied with falling profits, and are still less satisfied when no profit is being made. The question therefore arises: Is it possible to have a profit-sharing scheme so arranged as to steady the increment and thus remove that most serious obstacle? To that point I wish to direct my remarks. We are all aware that in the cotton trade a very serious position is arising. In April next the question of wages in the cotton trade comes up for review. Many of the leading cotton spinners at the present time are considering the advisability of a wage advance being made now in view of the great profits which are being made and the great increase of capital values. Some of them have told me that the only thing which is holding them back at the present moment is the great fear on their part that if the cotton operative's wage rises to a higher level there may be a reaction on the engineering trade. At the present moment the wages of engineers are less than those of minders in cotton mills. If the minders are to make more money than they are making now we shall certainly have a formidable claim from our engineers for higher wages. I have suggested that it would be impolitic in the highest degree for mill owners to raise wages if it can possibly be avoided, and that the proper thing for them to do is to use a certain proportion of these profits for the benefit of the workmen concerned. I suggest that a scheme of this nature might advan-

tageously be adopted by engineers. In the paper it is suggested that the rate-fixing and standard times might be dealt with by a Commission or by a Board with special reference to districts and towns. They will have nothing to do with the local cost of living but only with the geographical and climatic conditions and the producing capacity of the worker. Much the same idea underlies my suggestion, which is this, that in each industry a certain standard profit shall be agreed upon—a reasonable profit to the capitalist. When the amount of the profit is exceeded the surplus should be divided into two parts, one of which is to pass to the capitalist at whose works they are made, and the other part to the workers. Now here comes in the distinctive feature of my suggestion. The workers' share should not pass to the workers in the establishment where it was earned but *into a common pool*, and the common pool should be held in trust by some administrative Board for the benefit of the workers in the whole of the industry, to be distributed in some way to be mutually agreed upon. I myself would earmark the first distribution for the relief of unemployment. It is highly likely that in the near future each industry will have to look after its own unemployed workpeople. When the workers' share is distributed among the whole of the industry the total increase in the earnings of the workpeople would probably not amount to a large sum, but I do not think workmen would attach much objection to this. The evil of the present situation is that the workman emphatically regards it as unfair when excess profits are being made by the capitalist and he, the worker, does not get a direct share of them. Touching on the merit of the pool system, my brother had a scheme for individual profit-sharing at Bolton in an engineering firm in which he was interested. At the end of the first quarter the amount per man worked out at not less than £10, and £10 was promptly handed over to the workpeople. Within a week, by order of the trade union, the men had to refund it on pain of being expelled from the union. What was the trade union's objection? No doubt that the scheme violated their desire for flat rates and uniform conditions. Under the system which I have suggested all workpeople would receive a certain amount at the end of the year and if it were only £2 they would say: "It is not the amount of money that I value so much as that I have had a fair division of the surplus." That is the point that I wish to impress upon members—to earmark this pool for general distribution by a Special Board, even if necessary by the trade unions, with safeguards so that they do not use the money for propaganda or purely trade-union purposes, but in any case distribute it in such a way that all the workpeople in all establishments benefit to an equal degree in the prosperity of the industry. It would never do to let the surplus profit go to the workpeople at the establishments where it is earned. It must necessarily be distributed as a common pool, otherwise discontent would be rampant all round. I find myself in full agreement with the previous speakers that until such questions receive more consideration than they have done we shall not achieve the object in view.

Mr. D. L. Sands: I am quite in accordance with the views expressed by previous speakers regarding the human side of the business, and my only comment in regard to the paper as a whole is simply that it seems to ignore almost entirely our understanding of the psychology of the worker. That aspect of the question is almost entirely left out and I would point out to the author, if he is not already aware of the fact, that here is another variable with which he will have to reckon when he starts to introduce it into Scientific Management schemes. It varies in every district. In connection with time studies, the author refers to the question of the first-class man. I do not know whether the rate fixer is to be the first-class man specially referred to. If so, I can only say that in general the speed of operation of the first-class man is superseded right away on repetition work by a girl who has been on the job for two or three months. Another statement that I can scarcely agree with is that Scientific Management ceases to deal with labour as a commodity subject to supply and demand. When a job is commenced, how is the rate of remuneration to be settled? Usually by collective bargaining, the result of which I think will depend largely upon supply and demand of labour. Since my other points have been covered by previous speakers I will only refer now to the portion of the paper relating to Scientific Individualism versus Socialism. To my mind this whole section is grossly unscientific; it develops an irrelevant and unnecessary controversy. The fundamental principle of Scientific Management must be to secure the co-operation of the worker, which brings us to the position right away that in the latter portion of the paper the raising of the question of Individualism versus Socialism is really bringing out unnecessary antagonism. The true view of Scientific Management as it stands before us to-day is that it is the replacement of tradition and rule-of-thumb by considered methods based upon a study of the problem in general. I hold the average British workman in high esteem, and I do not think it is altogether in keeping with our prestige as scientists that we should start him on Scientific Management with a scathing condemnation of the present labour idols. In due course, if we pursue the right path, as we can do with Scientific Management, I think he will be man enough to see it and admit it.

Mr. A. P. M. Fleming: In considering matters relating to management we are prone to consider only the conditions arising in the factory. We must take a wider view, for as Mr. Mensforth emphasizes, the good of the community must be considered in addition to that of the individual worker and of the management. Men react to differences in social and domestic conditions, and this influences the work they do in the factory; motion study and fatigue study must take into account these variations, and not presuppose that a kind of standard man is being considered. It must also be borne in mind that the selection of men under the Taylor system is rigid and exacting, and I can conceive that in the vast majority of industries the methods that would be used to select men in this way would result in the choice of those of a similar type, and that there would necessarily be a considerable number rejected. We may therefore be dispensing

with the services of a number of men for whom the community will have to provide in some form or other. I should like to hear the author's views on this question of men who, while employable and employed under ordinary methods of management without rigid systems of selection, would find no place under a rigid scheme. I have had little experience of so-called Scientific Management in factories, but I have attempted on several occasions to chart the characteristics of men required for particular posts, and I have recognized that the difficulty of fitting men to jobs is so great that very frequently it is necessary to carry out the reverse process and fit the job to the man. In the majority of responsible positions both processes are undoubtedly at work. The attention now being directed to Scientific Management is such that younger men may become enthusiastic in the matter. To them I should like to utter a word of warning against the flood of literature that is now being poured out in book form on this subject, not necessarily under the heading Scientific Management, but under such headings as industrial administration, industrial economics, etc., much of which emanates from the United States and a large proportion of which is worthless. Men who have had the necessary experience to deal with the matter are usually far too busy to attempt it, but I hope that we shall obtain from them really sound literature which will accomplish for British management what Dr. Taylor tried to do for that which has arisen in the United States.

Mr. J. D. Paton: I think that Dr. Taylor should have the credit of being the originator of the movement, and that those who would detract from him are wanting in courage to handle the subject as he did. His experience is only what is common to the men who have had to handle men in any quantity and estimate the moral values of our voluntary acceptance of innovation by the workers in this country. We know a thing is right and we introduce it in our works. I challenge any manager here who has tried to introduce an innovation in his shop to say that he ever got it going on a voluntary basis. Truth is a straight line and no accommodating deviation has anything to do with Scientific Management. There is one glaring instance in Lancashire of the unwilling attitude of the worker to a very material advantage and social reform. In the Rhine Valley baths were introduced. They did not say to the men: "Will you wash?" They said: "Go in and get washed and come out clean" and the men did as they were told. In Lancashire an enterprising company also built baths. They could not issue orders but they expected the workmen to use them under the principles of voluntary acceptance. Who went there? A few boys. I think Dr. Taylor has handled the problem with judgment and given due regard to the amenities of the worker's life; no employer ever tried to do more. He faced the problem to establish the truth of work as the only road to evolution, and we want to handle it in the same way. Scientific Management equally applies to managers as to men. When an economic truth is established in industry its value should not be left to voluntary acceptance by a community incompetent to appreciate it; by physical discipline under correct conditions an involuntary recipient must eventually become an appreciative applicant. Taylor realized this truth and took the straight road to its application.

[The author's reply will be found on page 366.]

Discussion before the South Midland Centre, at Birmingham, 17 December, 1919.

Mr. A. Phillips: I may say at the outset that I am a firm believer in the application of Scientific Management as a means of obtaining that increase in production so essential to be brought about to the greatest possible extent at the present time. The author appears to consider that "Taylorism" is the only solution of all the troubles that the workshop is heir to. It cannot be denied that time study, the fixing of rates, and the elimination of all unnecessary motions in the performance of work will go a long way to reduce the cost of production; but I am inclined to think that Taylor scarcely visualized the conditions that are bound to obtain under what is recognized at the present time as "mass production," and this I think will require very careful consideration on the part of manufacturers who must apply it. The end and aim of Scientific Management is to produce the maximum amount of work with the minimum amount of effort, and this not only in the physical but also in the mental direction. The sub-division of work to such an extent that the people employed in it have only to learn one simple motion and continuously to repeat it in order to do this work, is a condition which is not calculated to stimulate the brain of the individuals who are engaged in it, and it is frequently stated by people who claim to be experts that this condition of manufacture will tend to reduce the numbers of skilled workers. It is also a condition of employment that is distasteful to a skilled worker. When one looks a little further it is obvious that the number of skilled workers, instead of being less, will be greater; they will, however, be engaged in producing the necessary equipment for the unskilled workers. The amount of production will then be increased by hundreds per cent. The field of unskilled workers will necessarily be leavened by many who will have attempted, but failed, to reach the amount of skill requisite for the more skilled occupations; also from the ranks of the unskilled operators on machines will arise undoubtedly (as well as from the ranks of skilled labour) men who will take high administrative positions in the works. I am one of those who believe that it is quite reasonable to have a condition in which people will carry out the purely mechanical and repetition part of production and need not necessarily regard their work as their whole life, but merely as a means of providing them with necessary bread and butter. Shorter hours, congenial conditions of labour, in so far as the sanitary and hygienic arrangements of the establishments in which they have to work are concerned, will, I believe, render those who work under such

conditions happier, realizing that they may enjoy and live a more full and happy life in their leisure time, which of course will be much greater than it has been hitherto. That it will be necessary for them to subject themselves to a certain amount of discipline they will readily agree to, when they realize the great advantages that not only they but the community at large will derive from this method of intensive production by means of machinery and a very fine sub-division of work for the purpose of reducing the amount of skill necessary. The thing that is requisite at the present time is to educate the people to realize the necessity of this condition. I see no reason why the great majority of those who are doing preparatory work to equip themselves for higher positions in other spheres of industry should not devote a part of their time to attending to the world's productive machinery, thereby directly benefiting themselves and also the community. The author has mentioned a system of payments by results as being the only satisfactory method of rewarding labour, and I understand him to mean piece-work. While, of course, payment by results is what we are all anxious to get, yet payment by piece-work is not, in my opinion, always the most satisfactory method of dealing with the worker, in a modern factory, producing a definite line of manufacture. It is quite possible to lay down plant and estimate with considerable accuracy the capacity of every machine in it to produce the components required: the only thing then remaining to be done is to select the operator who will run that machine at the speed and feed already decided. An individual system of piece-work would not be necessary, nor indeed advisable, as what is needed is a balanced number of parts: and this result is best attained by careful calculation of the number of pieces one can get with safety from any given machine. This method of course may still be considered a method of payments by results, but the great difference between this and the system of individual piece-work is, that although payments are made by results the results are predetermined and are not left to the initiative of the individual.

Mr. W. Wilson: It seems to me that a system of management is like a building. When a firm begins work, it opens a small shop, which is subsequently added to as necessities arise, addition after addition being made until, in the course of years, the factory has become inconvenient and rambling, and generally inefficient. In such a case the best policy is to discard the old building and to start afresh in an entirely new edifice. Our factory-system is in somewhat the same condition. It was founded many years ago, and has been added to and modified to meet changes in industrial conditions, but badly needs a root-and-branch revision. This revision, I consider, is amply provided by the system described by the author, which numbers among its many excellent features the fact that it begins from first principles and builds up a thoroughly satisfactory edifice upon them. Now to begin with, the basis of Scientific Management is a system of piece-work, and I should have been glad to have seen a little more space devoted by the author to an argument in support of the piece-work principle, especially as this system is practically illegal in some parts of the world. It so happened that in 1904 I was working on the same bench as a very prominent trade-union official, and had an opportunity of hearing the feelings of such people upon piece-work. These men object to it, conscientiously in my belief, on the grounds that it penalizes their weaker brethren, and I think some countervailing argument is necessary before we fly in the face of such opinions. Within recent years I have had considerable experience of both day-work, the bonus system, and piece-work, and have come to the conclusion that piece-work is thoroughly justified, principally because it gives the workpeople a direct interest in their work, and so converts the most monotonous operation into one which is capable of sustaining their interest. Much of the work done in our factories to-day is of this monotonous description, consisting as it does of the mass production of large numbers of similar articles. Most people who have had the direction of such work will have experienced the great improvement effected when the operators pass from day-work to piece-work, the quantity turned out increasing some times as much as 600 per cent through the increased interest that the operators take in what they are doing. On the other hand, there is no doubt that the piece-work system possesses serious defects, and my support is the more cordially given to Scientific Management because it is capable of overcoming these deficiencies. The latter are principally derived from the "humanness" of the rate-fixer, who is apt to make mistakes, when he carries out his work in the ordinary manner. The rectifying of these mistakes is the source of most of the friction which accompanies the piece-work system; and through the ability to fix prices by first principles, without the present rule-of-thumb methods adopted by even the most capable rate-fixer of the old order, nearly all the imperfections of piece-work are done away with. Another feature of Scientific Management is the division of the responsibility of a shop among a number of officials instead of its being entirely under one head. This is, I think, another great improvement. It is an exceptional manager who is able to keep in touch with all the work that is being carried out in the shop under his control; and unless he is in touch with the work, he is unable to criticize the products effectively and to help those under him. He is therefore at a disadvantage in superintending his men, and in order to make his authority felt there is a strong temptation for him to avail himself of the frailest pretexts for administering censure and so to degenerate into a mere bully. I feel very strongly that this kind of thing is much more responsible for industrial unrest than any other factor, including that of remuneration. A workman who is found fault with in this manner easily recognizes that his superior does not know as much about the work as he does himself, and he appreciates that he is being dealt with unjustly. At the same time he cannot "get his own back," as a manager is not a man to be argued with, and a strong feeling of irritation remains, and remains for much longer than is generally suspected. A series of such petty annoyances may occur during the course of a few weeks, each one serving to accentuate the discontent, which finds vent as soon as a tangible

question offers itself, and this is generally the question of wages. As the result of experience in seven different factories in two different parts of the world, I am certain that these and similar pin-pricks are responsible for nine-tenths of the strikes that occur, and the question of money is unimportant in comparison. The system we have heard described will go far towards obviating this, for it places over the workpeople men who are experts in their particular departments, and who are able to help those under them by their criticism and even by their censure. The stress which the author places upon a study of conditions in a factory also commends itself to me. It is astonishing to find the ignorance of such vital questions as lighting that exists even among those who have designed some of our most recent factories, and the question of efficient lighting is an all-important one from the point of view of accuracy of work and the well-being of the workers. I was once concerned in a factory where lacquering was carried out on a large scale, both by day and by night. During the daytime the light was derived from windows which were partly camouflaged with blue paint, so that the pale yellow lacquer was thrown more into prominence by the light blue tinge imparted to the daylight. As soon as artificial light was necessary, it was provided by ordinary metal filament lamps, furnishing a light approximating to the colour of the lacquer, which was in consequence nearly invisible. The result was that much of the work done during the darker portions of the day was condemned upon inspection, whereas the damage to the eyesight of the workpeople engaged must have been considerable. All this could have been obviated at very trifling expense as a result of a rudimentary knowledge of electric lamps and of the principles of lighting. Such experience could be multiplied almost endlessly and points to the conclusion that the average efficiency of work done throughout the workshops in this country could be increased by a very appreciable amount by the installation of this phase of Scientific Management. The author has asked for opinions as to the best manner for introducing Scientific Management. It seems to me that its introduction into a factory, preferably employed upon quick repetition work, would not be difficult and could be effected by starting with the rate-fixing department. It might begin in a small way and spread throughout the factory, the efficiency of which would increase so much that it would be a strong incentive to other firms, which were in a position to be familiar with the first one, to adopt it also.

Mr. C. Bell-Walker: I wish to refer only to that aspect of the question bearing upon labour unrest. I am of the opinion that the cause is mainly psychological, and increased pay and efficiency will not cure but might possibly aggravate it. The best work is rarely performed with the object of making money, but arises from a pride and interest in it. I may instance, as an example, the fact that a large proportion of the nation endured unparalleled suffering and privation during the war for practically no pay and that no financial inducement would have so stimulated them. The danger of the Taylor system to my mind is the tendency to reduce men to the level of parts of machines. This is perhaps not inevitable with this system, but I fear the tendency. I am also of the opinion that a piece-work system of payment, although at the present time the most successful and practicable, is not the system that should be aimed at, because the workers' and employers' material interest are antagonistic, the former's being to do the least amount of work for the greatest amount of money, and the latter's to give the least money for the greatest amount of work. It has never been proved that high wages in themselves are a cure for labour unrest.

Mr. J. A. Hannay: I hope the author is not going to make the mistake of holding out a promise of a speedy solution of the capital and labour problem by Scientific Management. It has taken very many years for the present difficult position to develop, and it will take a great many years to solve the difficulty. Both capital and labour will have to be patient, trust each other, and work together to bring about a satisfactory solution; and Scientific Management will undoubtedly play a very great part in that solution. Whilst the author has covered a very wide field he has omitted to mention a very important and essential matter, namely, the educating and training of young men who are preparing to enter into various industries. I consider our educational means to be totally inadequate, and before we can expect to get really Scientific Management, I think that a great many of our schools and training colleges will have to be overhauled and re-staffed. In my opinion it is a scandal that the teaching profession is not better supported and the very best possible teachers selected to train young men who in a few years will be entering on their business careers. I entirely agree with Dr. Taylor and think that the differential piece-rate system should be more generally adopted. Looking into the future I consider that Scientific Management in the engineering industry will involve more and more attention being paid to tool room, jig and tool design, and equipment, and I am quite sure there should not be the slightest cause for anxiety on the part of the workmen in developing improvements to the greatest possible extent. This is where we shall eventually find nearly all our skilled men. The want of an adequate supply of skilled men is preventing our tool rooms from being thoroughly developed, and results in the loss of a very large amount of production. I wish to emphasize the fact that, if capital and labour can only agree and concentrate more and more on tool equipment, this will automatically solve innumerable problems. Some people believe that labour objects to repetition work because it is uninteresting, but I do not think there is anything to fear from this provided the worker is adequately recompensed and is able to work under healthy conditions. Dr. Taylor said that operators must be trained and that if they did not prove suitable others must be trained in their places. This is, however, a very difficult matter to carry out in a works already established, and I should like to hear what the author has to say about holding up production and putting the factory out of balance while fresh labour is being trained. To me it appears that there is only one way, namely, to make the operations as simple as possible

and to provide adequate tools. I agree with Dr. Taylor that in large works the position of works manager is not as necessary as it used to be. What is required is a number of departmental experts as outlined by Dr. Taylor. The extent to which Scientific Management can be adopted depends entirely upon whether the financial side will give the necessary assistance, and, unfortunately, in many instances such assistance has not been forthcoming.

Mr. H. Soper: The author suggests that industrial research organization should be set up on national lines, and that the national council should appoint territorial district councils and so on down to the individual works; in other words that the conversion should be from above downwards. Practice has proved that in individual works the installation of Scientific Management is best carried out by starting with a small section and using that section as an object lesson to convert other sections, until the whole has been converted. In view of the distrust with which Scientific Management is at present viewed by uninformed persons, both employers and employed, I suggest that if the Government is to take up the work it should commence with a number of model factories at which both employers and trade-union representatives could familiarize themselves with the subject. I am of opinion that any rate fixed should be considered to be binding unless the operation itself is changed or there is a general reduction in the cost of living. It is the cutting of rates which has rendered the introduction of Scientific Management into this country so extremely difficult. The "Ford" method of wage payment is to create a flat day-rate so much above the average paid in the district that it is not necessary to pay an individual bonus in the works in order to get increased output; but this can only be done by individual firms and under exceptional circumstances, as if other firms followed along similar lines the incentive would disappear owing to the rise in the district rate.

Mr. A. Krause: In my judgment opposition to Scientific Management comes less from workmen than from their intellectual superiors. The workman's objections are two-fold, the first reason being that he is unscientific—for which his poor education is responsible—and the second is his fear that higher efficiency will lead to his unemployment. I believe that if he has a guarantee against this eventuality he will accept Scientific Management. The opposition from the managerial and proprietor class is principally due to unscientific training and, in some cases, to a wish to leave well alone. Some people object, on grounds of its imperfectness, to the system proposed by Dr. Taylor, but I suggest it is really unscientific to expect a cut-and-dried system to apply to all cases. One may as well decide never to quote a fixed price for work because costs and estimates are imperfect. To obtain data from experience can do nothing but good, however sparingly they may be used in its early stages. One might almost liken Dr. Taylor's innovation to research applied to industrial matters. What we owe to research is only just being realized. If one postulates a saving of 25 per cent of human effort in producing the world's present services one can realize that it is equal to the saving of effort or increase of productivity resulting from many years of invention.

Mr. N. Martin: Lord Kelvin used to tell his students at Glasgow University that nothing could be really known of any subject until definite quantitative standards of measurement had been established, and methods of measurement got into use. I have always regarded the researches of Taylor as an attempt to set up standards of measurement for that most elusive of all quantities—human activity—and I regard his work as the opening of a new era in industrial history, when instead of being content with a rough quantitative idea of the amount of human activity, based on financial results, an exact quantitative analysis could be made beforehand of the amount of activity required to produce a definite result by standard methods. A previous speaker has said that no system would avail if the workers were not interested and keen on their work. From what I have seen of the Black Country I am of opinion that a very large proportion of the workers are employed performing operations on repetition work, in which no natural human being could be permanently interested. They, like most of us, work not for the intrinsic interest of the work, but to earn their daily bread, and to do so have to be content to perform a greater or less amount of daily drudgery. But it is just here that Dr. Taylor's work holds out the greatest hope for the worker. He has shown the method of attack that promises to yield the greatest result from the least effort, and if the worker is not robbed of his share, Scientific or "measured" Management, based as it is on ascertained fact, seems to me to offer to the worker, without increasing the monotony of his work, a greater reward for his labour, and thus assist him in some measure in escaping from the dreadful monotony of life that is the portion of so many workers.

Mr. W. H. Edwards: I entirely agree with a previous speaker who remarked that Scientific Management has for a long period been used and improved upon by firms in this country. There are, however, hundreds of factories where no system such as that described in the paper is used, while in some instances various systems are used, even in the same factory: one department will be up to date, another using ancient methods, and various intermediate stages in the several departments. This chaos is due to our conservatism. When we develop improvements in methods they are kept strictly secret. Instead, we should consider our industries from a national viewpoint and exchange ideas more frequently, encourage visits to various works, freely criticize and copy to our mutual advantage. One point omitted from the paper but referred to by one speaker is of great importance to the ultimate success of any scheme of industrial improvement, viz. the education of the skilled man for such positions as manager, supervisor, foreman, designer and toolmaker. What can be offered instead of apprenticeship? Many boys who have had a technical-school training find it difficult to get into our large works unless they are satisfied with being put at a repetition machine and their efforts thus stultified. Manufacturers and others must offer facilities to such students, or the initiative so necessary to keep Britain

in the van of the world's engineering industry will surely suffer the consequence of their indifference to the demands of futurity. Let us look after our skilled men and the unskilled will look after themselves. The main object of the paper appears to be to bring all firms into line by nationalizing Scientific Management. Of course some disadvantages will occur, but universal adoption of the scheme will result in greatly increased production, if the workers can be induced to co-operate. This can only be arranged when complete confidence is obtained between employer and employee. Judging by past experience the worker expects piece-work rates to be reduced immediately he obtains a good percentage above a living wage and by his own skill and energy penalizes his less fortunate fellow-worker. I maintain that confidence will only follow a definite arrangement to fix a price, prove it, and allow no alteration on either side, unless the machine, material or other conditions are improved to warrant the change. I have often seen operators working with identical machines and under identical conditions where A can earn only the minimum rate while B will earn 50 per cent over the minimum with less damage to tools and equal accuracy. Here is evidence that the skill and energy are the asset of the operator, who should be paid for all possible results of effort without fear of reduction in piece-work prices. The Taylor system calls for the most suitable man for the job, but the line of demarcation is difficult to locate, as health, temperament and physical development and deformity are important factors which without tact and judgment may be carried to extremes. I will illustrate this point by recalling an article in the *American Machinist* some years ago when Taylor's method was being followed strenuously at Bristol (Mass.). In two factories in competition, several small parts had to be assembled together and manager No. 1 realizing the advantage of using both hands to pick up work from a tray on each side of the operator to assemble on a piece in front, conceived the idea of advertising for dexter-handed operators. Manager of Shop No. 2, improving on the idea, sought to cut out the waste motion of the head movement in following the action of the left hand, then right hand, to finish in front, by advertising for dexter-handed cross-eyed operators. The moral is obvious.

Mr. W. H. Heaton : The author has certainly made out a good case for the introduction of Scientific Management into the works of this country, but there appears to be rather an important omission in the paper. In the first place, what really do we mean by Scientific Management? It may not be expressible in a short crisp sentence, it may be open to several definitions, but it has one aim. The aim of Scientific Management, as I conceive it, is to establish 100 per cent efficiency in every worker within a works. Now, what really do we mean by 100 per cent efficiency in a worker, and by what means do we attain that end? I think, first and foremost, the question of the attitude of the worker to his job must be a correct one. It seems to me that all systems of organization and supervision are valueless if the work is not mentally attractive to the worker. Accepting this, it appears that the fundamental and root idea of Scientific Management is based on the soundness of judgment exercised by the management in the selection of men for the work they have to perform. Discontent must be eliminated in all forms from the lowest to the highest worker in an organization, and this is of paramount importance. To my mind, Scientific Management which makes for greater efficiency does not rest merely with shorter hours and higher wages. I should like to have heard something in regard to preserving the standard of quality of the product manufactured. Merely to increase the output, which might in certain cases mean a corresponding sacrifice in quality, is, I feel sure, not intended, and therefore whilst shorter hours and higher wages are the results to be achieved, we are bound to make the corresponding efforts to preserve and maintain, and, in some cases, improve the standard of excellence of the articles we are engaged in manufacturing. I should like to say in conclusion that the paper contains suggestions which are really welcomed by those engaged in the management and control of factories.

[The author's reply will be found on page 366.]

North-Eastern Centre, at Newcastle, 12 January, 1920.

Mr. A. D. C. Parsons : This paper has been produced at a very opportune moment. We in this country are confronted with conditions so totally different from those which we were accustomed to in pre-war days, that we are now compelled to reconsider our methods and organizations with a view to seeing what modifications may be necessary to meet these new conditions. Dr. Taylor's system of Scientific Management has undoubtedly received more attention in America than in this country. Perhaps this is only natural, since the cost of labour there has always been high compared with other countries, with the result that the demand for labour-saving devices has been encouraged, thus causing a ready market for standardized machinery. Furthermore, they have a very large home market in which the manufacturer can dispose of his goods. Standard manufactures naturally call for specialized organization, and with the exception of a certain number of firms who have had business connections with American manufacturers, we, as a country, have not gone nearly so fully into the matter as America. Here on the North-East Coast we have up to the present, with the exception of the war period, not been accustomed to a great deal of repetition work, which makes the adoption of a highly specialized organization a matter of very considerable difficulty; but I am very interested in what the author has said in regard to shop and office organization on page 337, as this very closely resembles the methods adopted by the firm with which I am associated. He has rightly pointed out that in starting such a system there is the danger that, when evolved and put to work, it may degenerate into a system

where the smooth running is absolutely ruined by the movements being clogged with paper. If this happens, both the shop and office lose faith in the method and ignore it. Build up the system gradually, get the people who are working it enthusiastic and let them realize that it is they who are running it; then we shall find that production is assisted. I should like to describe in some detail the system we are using. When an order is obtained for delivery by a certain date, the time between the date of order and date of delivery is apportioned out to the various manufacturing operations such as obtaining the raw materials, making patterns, etc., for all principal parts comprised in the taken for the various operations are actual instead of estimates. By using such a graphical method it can be readily seen whether any part of the machine is backward and liable to cause delay in the completion of the whole. Furthermore, it shows clearly whether the drawings, patterns, material, etc., have been delivered up to time. In actual practice the diagrams used contain considerably more items than those here shown, but this is sufficient to illustrate the method adopted. Although only the main parts are shown on such a diagram, careful track is kept of all other details by means of detailed progress sheets and detailed specifications embodying all manufacturing information.

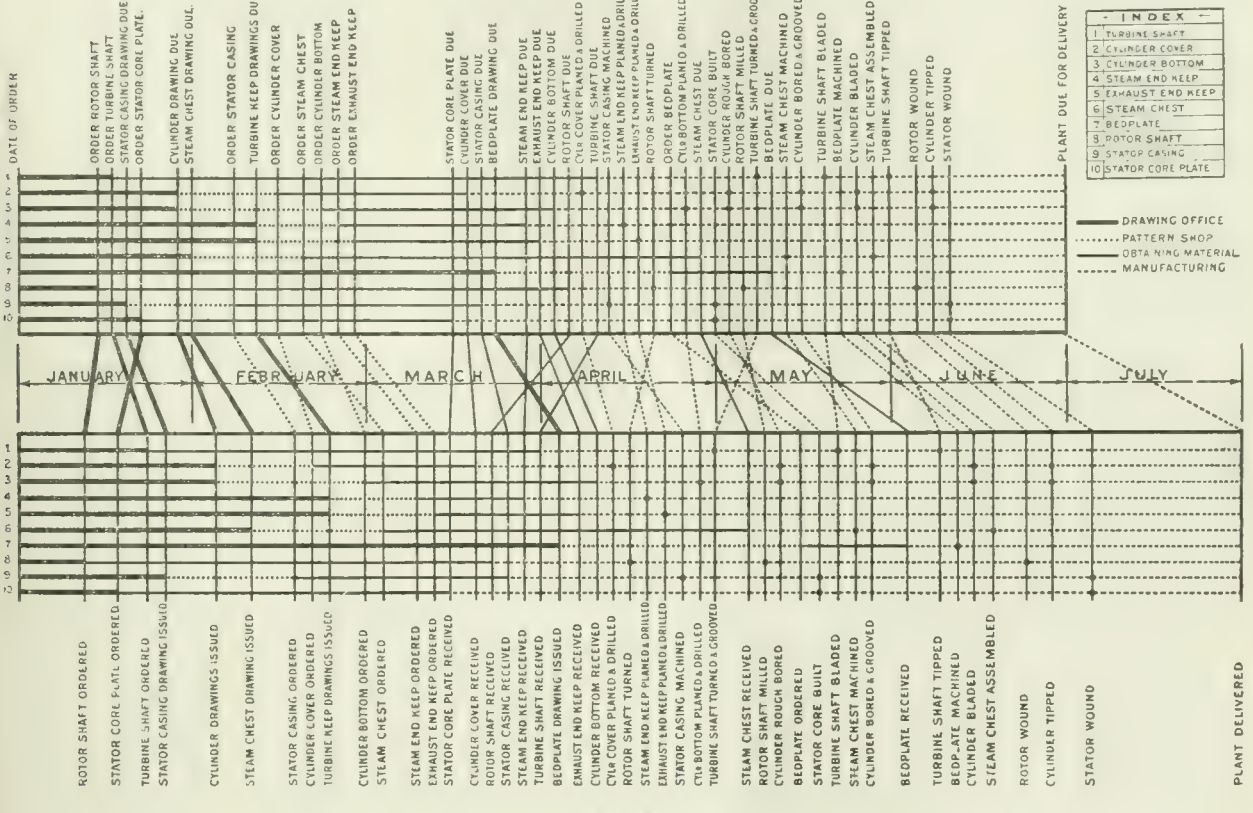

FIG. A.

machine. The method of doing this will be seen in Fig. A herewith. The upper half of this diagram is the result of so apportioning out the time for each main item; the drawing-office time, pattern-making, time taken to get raw material, and time for manufacturing are all depicted by differently graded lines. All the drawing-office work is shown by thick black lines, whereas the manufacturing is shown by dashes. In practice, colours are used to distinguish between the different operations. The top half of the diagram is therefore an estimate of the time taken to manufacture the plant in question. As the manufacture proceeds the top half diagram is connected to the bottom half by similarly graded lines, and a similar diagram is produced in the bottom half, except that the times

With the diagram referred to above, specification sheets, and progress sheets, the production department has full information on the condition of all parts comprising the turbine, but in addition to this it is necessary that the progress of work should be kept careful track of throughout the factory. This is done by the detailed specification sheets, and also weekly work cards on which are marked every complete operation due out in any one week. By this means it is easy for anyone to see, after a short inspection of such cards, what the condition of any department is. The aims of such a system are as follows:—(1) To prevent delays. (2) To control the supply of materials so that they are received when required, not too early or too late. (3) To prevent any part of the work getting too far advanced, so as

to minimize as much as possible the capital locked up. (4) To bring forward each part of the machine so that it is ready for assembling when required: this is very important. Men work better, and work goes through more quickly, and therefore costs less, if parts come through when required. Turning again to the paper, the author on page 330 says, "All the devices used in office and shop as means of efficient production they consider in the same light as mechanisms, i.e. of secondary and not primary importance." Personally I consider such devices as I have described to be of primary and not secondary importance; they are absolutely vital and form the very foundation of any production system. Then again, on page 331, the author refers to the Government report dealing with "A study of improved methods in an iron foundry." Can he form any idea as to how much of this wonderful increase in production is due to arranging the supply of materials so that they are on hand when the workers require them? In regard to payment, there seems to be only one satisfactory method, namely payment by results, and it is hoped that the time is not far distant when such a system will be universal. If, by using the methods laid down in the paper, production can be increased and at the same time, as the author suggests, a solution of the capital and labour problem can be found, and if this can be done before it is too late, then undoubtedly this country will realize a state of prosperity which has never yet been equalled.

Mr. T. Carter: The paper raises many questions, any one of which could profitably have a whole evening devoted to it. One of these, for example, is how far inspection should actually go, whether one should make a point of inspecting every single thing that comes into, or is manufactured in, a works, or should inspection go only so far as from time to time seems necessary and be extended when difficulties occur? Another such subject of inquiry would perhaps be the details of the application of the system to technical work in the office, which is not very fully dealt with in the paper. One thing must be clearly understood, viz. that employers have at least as much to learn as their workpeople have, and I can quite imagine that some employers are extraordinarily ignorant of even the first principles of management. The system is not merely common sense, but is rather the application of hard thinking by experts, with experience and real common sense behind it, on a definite plan and for a definite end, which is a very much more precise thing than merely the casual tackling of the problem, even by the best common sense, in an untrained way. Each of us has his own characteristics, and I believe that each of us can find out for ourselves, by experiment, what they are, better than anyone else can tell us. It is, however, necessary that there should be some preliminary guidance, and that is where the expert comes in. These experts, however, must be of the proper sort, and the author very rightly points out that engineers ought not to be expected to be experts on physiological or psychological problems. One of the wrong sort of experts has, I am afraid, been the welfare superintendent. The help of both employers and workmen is very necessary in the problems that have to be faced, and simple suggestions made by employees may have extremely important results. I have two suggestions to make. The first is that problems and their suggested solutions should be explained rather to individuals than to masses of men, as I cannot help thinking that if one could produce a strong impression on a few minds it would be very much more important for the subsequent development of the subject than to produce a weak impression on a larger number of minds, with the same total effort. Conversation with individuals in a friendly way at home, and quite away from the surroundings of works or public places, would have extraordinarily good effects, and the mental attitude thus induced would act as a leaven throughout the whole lump in a quiet but remarkably effective way. One of the chief difficulties is that so many people do not understand the problems that are being raised and think them very difficult, or wrong, or even harmful, merely because they do not know. The second suggestion I have to make is that the staff, who are a body intermediate between employers and manual workers, could probably be used in many at present unrealized ways to elucidate such problems. They have, unfortunately, been left out of the scheme of Whitley Councils, and have at the moment no very particularly recognized position in the scheme of industrial affairs as a whole, but the very fact that they are, by their position, able to see both sides—very often in a way which is not possible either to employers or to manual workers—makes them peculiarly fitted to bring to one side the views of the other in an intelligent way. Such points as those of a capital levy, or of finance generally, or of the conditions of living of the working classes, or facts about capital, could often be easily explained to those who have not hitherto been in a position to understand them by even the less highly instructed members of the staff. The hazy notions about capital could frequently be cleared up and people could be taught, for example, that capital is not necessarily money, but that such a thing as co-operation may be capital. The author mentions that the majority of people do not yet understand the significance of the phrase "survival of the fittest." Young men think that the fittest are those whom they recognize as morally the best. That, however, is not the case, and the best man, who, under the author's scheme, is to be compensated more than the average man for his work, may actually be—from the point of view of society—the greatest villain. This is part of the anomaly of the stage of evolution at which we have at present arrived, and it is for us who see something better to step in where we can and improve matters, so that eventually we may arrive at some great scheme of co-operation under which the word "fittest" shall be synonymous with the word "best."

Mr. A. McL. Ranft: It seems to me that the word "scientific" is superfluous, and that "management" is comprehensive enough. There can, of course, be good management and bad management. We Britishers have always been prone to cry out that we were not so up-to-date as other nations, but this system of fixing rates for engineering work by means of splitting a job into elements was not unknown on Tyneside as far back as 1889. It may have been known under a

different name, but the essential points were there. In my opinion, the author's explanation of opposition in America to his so-called "Scientific Management" appears to be more complex than political. Is the explanation not due to the members of the trade unions and their leaders thinking that the methods proposed by Dr. Taylor would have the tendency to make them mere automatons? It cannot be denied that this splitting up of work into details must of necessity control, or try to control, every movement of the worker during the whole of the working day. On pages 332 and 333 the author gives percentages of time which, upon close examination, I find from experience do not agree with many examples of work done in a large machine shop; it would be of great interest to have full details of the actual job on which the handling of the tools represented 75 per cent of the total time occupied on the job itself. Motion and time study are in themselves very interesting, but the human element is variable, so that to standardize detail times for work from data thus obtained requires very careful handling. The author deals with this matter from a very decided point of view, and, personally, I cannot agree with his conclusions. I consider that we should endeavour to train apprentices on the right lines, demonstrating to them the correct way to obtain the best results, as it is known in all walks of life that to take an adult and endeavour to change his habits is somewhat difficult, whereas apprentices are in their plastic age and the cultivation of the highest thought on the qualities of craftsmanship would, in my opinion, bring about during the next few years a great change in the attitude of the workers. On page 335 under "Payment-by-Result" the author tells us a great deal of what should be done; it will be of interest to mention that such methods have been in vogue for a considerable time in engineering works on Tyneside. The author says that where a price is agreed upon between the Rate Fixing Department and the men and a disagreement afterwards occurs, it can be easily rectified. He must have a very persuasive way when dealing with these matters, as those of us who have had these difficulties to get over, have long ago come to the conclusion that easy is not the correct word to use. In conclusion I can only say that the best results for both employer and employee will be obtained by co-ordination and co-operation.

Mr. B. Bedworth: It is nearly 20 years since Dr. Taylor introduced his so-called Scientific Management, and we must not lose sight of the fact that a great change has taken place in the relation between capital and labour during that time. For any system to be successful it must first receive the support of labour, and if labour is to approve of it, it must be able to show that, by the system, labour will gain not only financially but mentally and physically. Does this system fulfil these conditions? I think not. First, how will it benefit the worker financially? We have a system (on paper) by which, if correct, it is possible to determine beforehand the absolute capacity or output of both man and machine. If this is true, how much are we going to give away to labour? Second, how will it benefit the worker mentally? This system robs him of his individuality; everything is already thought out for him right down to the smallest fraction. It is a new idea to me, if by retarding a person's thought we can increase his mentality. Third, how will he benefit physically, in so much as it is necessary for him to perform a certain operation in a given time? My own idea of the right kind of Scientific Management is simply applied common sense, of which Mr. Parsons has given a good illustration. What good will it do to have an elaborate system of feed and speed if we have not the material to feed our machines? What benefit is it to know just how much our assemblers can do, if we do not supply them with the parts to assemble? In conclusion, I would say apply common sense, feed the machines, cut out unnecessary waste and delay, and study the interests of the workers as well as one's own.

Mr. E. E. Grover (*communicated*): The author on page 332 mentions that the foundation of the system is a study of motion and time which assists in eliminating, as far as possible, waste of time and energy and enables piece rates to be fixed. It would have been interesting to hear some details of the methods of measuring the time and motion, and also some practical experience obtained in the study of the fatigue or rest factor. I believe it is generally admitted that up to a certain limit, and with a given number of men, the output of a shop can be increased by a reduction in the hours of work. The term "speeding up" I take to mean, not urging the worker to a greater physical effort, but seeing that the machinery is run at the most efficient speed, that the cutting speeds of the tools are correct, that unnecessary labour and movements are done away with, and that all unnecessary waiting for tools, cranes, etc., is eliminated. It therefore seems that the shorter working hours and "speeding up" are essentials of Scientific Management. There is another factor which is very important and is largely responsible for the difficulty experienced by the trade unions and the workers in agreeing about the benefits of Scientific Management. It is not possible to ignore the existence of the human factor and to regard the workers as machines. This human factor and the mental attitude in a shop have a very strong influence and give rise to the following objections among the workers: (1) Scientific Management may temporarily displace labour; (2) The workman lives from week to week and has no security of job. This may prevent a man doing his best even when piece rates are fixed; (3) The trade unions and the workers both dislike competition between man and man in the same shop. This is an obstacle at once to the time and motion study and to fixing piece rates. The only solution I have heard suggested for these objections is one known as the Priestman scheme, where the underlying idea is that of team work in place of the ordinary individual competition. That is to say, the system is one of payment by results on the basis of the whole output of the shop. Having fixed a certain output as the standard, if the actual output is then increased by, say, 20 per cent in that particular shop, the wages throughout that shop are increased by 20 per cent, i.e. the day-rate wage can be increased by a percentage equivalent to that by which the average output exceeds the standard.

It is suggested that everybody in the shop is then interested in obtaining a good output. It seems that some system like this which provides a sort of team work on the principle of all in the shop doing the best for the shop, would produce more interest and more contentment among the workers, and would greatly assist in the carrying out of proper Scientific Management.

Captain J. M. Scott-Maxwell (*in reply, communicated*): Scientific Management is not a cut-and-dried paper system, with clearly defined rules and regulations applicable alike to all kinds of factories. If properly applied, it is most unlikely to be the same in any two single workshops. The details must vary with and be adapted to the local conditions. A large number of reliable books on Scientific Management are now published, and every week the technical Press, both British and American, has many valuable articles describing its actual application. The criticism of this paper may be divided into the following broad headings :—

(1) Criticism of the method of dealing with the subject, including objections to both the main and sub-titles; also criticism of such digressions as "common sense," "survival of the fittest." These are all of secondary importance and I only place them first in order, as it seems more convenient to get rid of them.

(2) Criticism of Scientific Management in its relation to the handling of labour and alternative suggestions, such as collective profit sharing. This part of the subject is the main object of my paper, and is of the utmost industrial and political significance.

(3) Criticism not directly concerned with the labour question but dealing with such specific facts as costing, quality, mass production, question of tolerances, supply of material. These are all important, but of secondary value to the preceding paragraph, from the point of view of this paper.

(4) Criticism of the opinions expressed on country factories, labour as a commodity, and the question of American versus British methods. Such digressions are of importance from their general and wider interest.

(5) Criticism of the scheme of national committees and some alternative suggestions.

(6) Suggestions regarding education.

Criticism of the Method of Dealing with the Subject.

I agree most readily with Mr. Stavenhagen when he says—"It will be found that everything finally has some definite relation with the political side of life." Politics and industry are now so inextricably interwoven that it is hardly possible to disentangle and thus deal separately with political and industrial problems. They must now be considered as different aspects of the same national and international problem. It is because so many industrialists and engineers refuse to recognize this situation, or if recognizing it, refuse to co-operate because they so distrust the politicians, that the politicians are left to themselves to legislate on matters of which they have usually no first-hand experience. The intention of the paper was not to indicate how Scientific Management can be applied in individual factories, hence I have not dealt with details. I am not interested in urging its general adoption so that more profits may be made. That to me is incidental to the most vital of all its possibilities, namely its political significance as a system for raising the status of labour by means of more efficient production in such a manner as will give more leisure, more money and higher education to the workers. I have therefore only described the fundamental principles of Scientific Management in its treatment of labour, because this still forms the storm centre of all discussion. The sub-title is intended as an indication of this. The intention was to treat it in such a manner as would arouse the maximum of discussion. In this, it would appear, the paper has been a success. It has been printed in practically all the engineering and management journals, and notice given to it in many local newspapers. Most editorials have been favourable and encouraging, and a few even enthusiastic. The paper has been discussed in the five largest engineering centres in the kingdom. The meetings have all been large, and although the printed discussion is lengthy, many would-be speakers never had a chance to speak at all, although everything was done to give the maximum opportunity. The evidence therefore seems fairly conclusive that there is a genuine and widespread interest in this subject, especially amongst the younger engineers, and that such interest is in great contrast to the complete lack of interest in pre-war days. Those in agreement with me do not require to be answered, but I wish to acknowledge the many kind and encouraging opinions freely given by so many speakers, but according to custom not printed in the *Journal*. I am a manufacturer and have no professional interest in pushing this subject. It is propaganda work, done out of normal working hours, in the hope of arousing more interest in the subject of management, not only in the interests of the engineering, and especially the electrical engineering industry, but also I hope in the national interest. There is little question of our great material resources and of the unique position we now hold in the world, but position, power and prestige are not enough in themselves and will not guarantee continued success, without in addition that progressive development due to the continual application of new ideas. Those in agreement with me have read my paper with care and attention. Those in strong disagreement do not seem to understand the subject of Scientific Management and consequently ignore almost everything I say. I admit that it is very difficult to concentrate and read with care where strong prejudice exists. Fully aware of this mental attitude I have already answered almost all the points raised by such critics, as a careful study of my paper will prove. Frank criticism is what is wanted, but complete ignoring and perversion of an author's statements is, from the engineering and national point of view, regrettable.

From the psychological standpoint such criticism is both interesting and productive. Being so negative, it creates a positive reaction, and thus acts as a strong stimulus, very necessary and complementary to the backing of one's supporters.

Objection to the name of Scientific Management.—Several speakers (Messrs. Atkinson, S. Mavor, Martin, Record, Keachie, Pettifor, Ranft) have objected to the title, including friends as well as foes, but there is an extraordinary paucity of suggested alternatives. That objection should be taken to the title, as suggested by Mr. Pettifor, because it implies that all other systems are non-scientific, seems reasonable at first sight, but only those systems are scientific which in addition to the scientific handling of material also apply analytical and synthetic methods to the measurement of the human energy expended in doing useful work. Without this, no system, however scientific it may be in other respects, can claim to be scientific in its treatment of labour. Rate-fixing without motion and time study is like analytical chemistry without quantitative analysis. That is the fundamental principle regarding manual and clerical labour. The other fundamental is the application of the same principle to the brain workers, namely the analysis of non-routine work into definite functions and the allocation of as few as possible distinct functions to suitable individuals. There must be more and more specialization in management. The highest form of management should be an art, but all highly developed arts are founded on a scientific technique. At present, management is neither a science nor an art. It is still in the early stages of groping after the truth, and when it does eventually develop a technique it may then become one of the arts. Dr. Taylor's system is the first to embody these two fundamentals, and any other system which includes these is scientific, no matter how the details may vary. Mr. Martin says Scientific Management is "just a phrase." I presume he also refers to the sub-title in his opening remarks, in which case I would point out to all who have criticized the sub-title, the difference between the definite and indefinite articles. I do not say that Scientific Management is "the" solution, but is "a" solution. Bigger things than Scientific Management are also necessary before we can hope to reach nearer to the goal of higher intellectual, moral and spiritual outlook. The materialistic movement of to-day can only be controlled by a great spiritual movement. The American origin of the title seems to worry some, but the American engineers experienced the same trouble. It seems a clear case of the "survival of the fittest." Surely, however, to worry so much now about the name seems rather a belated storm in a tea-cup. We are past the christening stage, almost past the wild-oats stage. It is now time to get to serious work.

That Treatment of Subject is unscientific, lacks definitions, is speculative and theoretical and makes "astounding" claims.—Mr. Paul says my method is unscientific because I confuse work and effort by stating that "Scientific Management makes it possible to measure labour effort accurately." He says: "It does nothing of the kind, being founded on payment by time." Mr. Paul, belonging to the old school of management, which was and still is only concerned with the quality and quantity of the work done, overlooks the very important new fact that Scientific Management also concerns itself in addition with the quality and quantity of the energy expended or the effort put forth by the workers in doing the work. Scientific Management does not propose to pay for all this effort—it pays for the result of the effort, but bases the payment on the useful effort component. It protects the workers from their own ignorance and assists them by applying the results of experimental physiology and psychology to their efforts, mental, nervous and muscular. It endeavours to save the worker from useless effort, and thus makes shorter hours and higher wages economically possible. To maintain that the workers can do this of themselves, without any education, training or assistance, is no longer tenable. The tendency of Scientific Management is to pay more for less effort, but to pay less for more work. When a movement is in a state of initial flux, definitions may or may not be a blessing. I went the length of adopting a definite name and this discussion is sufficient proof of the antagonism aroused. I purposely did not give any short definition, as I hoped the paper as a whole would form the best definition. I have given very briefly the history of the name and the movement, and as I was not writing a book, it was very necessary to limit myself, and I decided therefore to deal almost exclusively with Dr. Taylor's work, because he was the pioneer and American engineers first applied the name Scientific Management to his system. Because he is extreme—like most originators—I thought that the essentials of his system would be more readily grasped by those unacquainted with the subject, just because it is the greatest departure from the old or present system. Mr. Robinson's definition from Webster's Dictionary—"judicious use of systematic knowledge to accomplish an end"—seems rather too vague ever to become popular, and I take it any definition of such a subject should be clear to all concerned. That given by Mr. Vines seems to me rather long, and yet it is not altogether lucid, and does not cover everything. The functionalizing of the brain work seems to be omitted unless "process" also applies to brain process, in which case it is not very clearly stated. Also Scientific Management is by no means limited to "a factory." It is applicable to agriculture, to domestic housekeeping, to most of the professions and especially to the art of government, whether in labour unions, employers' federations, municipalities or Imperial Government. I still feel that short definitions will tend to make the situation more and not less difficult. It seems to me that we are fighting against a subconscious antipathy which must be overcome by strong counter suggestions, whereas definitions are apt to arouse intellectual criticism tending to maintain the present mental attitude. I am reminded of a worker who once remarked to me, as if it were a grievance, that we had no printed rules and regulations in the works, and then added that as soon as we had he was going to fight against them. I had that worker in mind when I steered clear of definitions. Mr. Stubbs says

my paper is speculative. I take that as complimentary because all new ideas are more or less speculative. There seem to be too many people in this country afraid to take the smallest risk. Huxley has said: "Men are beginning, once more, to awake to the fact that matters of belief and speculation are of absolutely infinite practical importance." Mr. Martin mentions four "outstanding bug-bears": (1) the implacable employer; (2) the irreconcilable agitator; (3) the bureaucrat; (4) the impractical theorist. He then says: "I fear the author is more of a theorist than any other." Than any other what?—bureaucrat, agitator or implacable employer? His first five questions are answered in my paper and the whole plan of the paper is to suggest how his last five questions might be answered. I do not "deprecate the idea of the survival of the fittest." I might as well deprecate the theory of gravity. What I do deprecate is the conception of "fittest" and "best" as synonyms. We must have standards of what is "fittest" and not leave it to force and chance. We must see that industrial and social evolution progresses and does not retrogress. Progress by evolution necessitates the continual shifting of the struggle to a higher plane. Civilization is still struggling on the plane of material subsistence. Mr. Martin is "astounded" at my claim that Dr. Taylor did originate something new, and says surely I "must be aware of the enormous strides in efficient production made by British firms before Mr. Taylor was born." I do not claim that Dr. Taylor invented everything in management and no one else anything. I claim that he is responsible for the development and application of motion and time study, and functional management, and if these ideas have been independently developed by the firms mentioned by Mr. Martin and by firms on Tyneside (Mr. Ranft) there is no written record of the fact. I thought that my digression on "Darwinism" would be enough to explain my conception of "new," but apparently not. If Mr. Martin is willing to agree that the steam turbine, instead of being a new invention, is 1,800 years older than the reciprocating engine, because Hero of Alexandria made and used a turbine to move images, about the beginning of the Christian era, or just 1,900 years before Parsons's invention, then I will agree that Taylor also did nothing new. Mr. Bedworth speaks of Dr. Taylor's "so-called Scientific Management" a system "on paper" as being introduced nearly 20 years ago. As a matter of fact it is 25 years since the first paper on Scientific Management was published. The system itself was worked out in the workshop—not on paper—over a period 15 years earlier.

Scientific Management and Common Sense.—I have never suggested that Scientific Management is "opposed to common sense." Some seem to misunderstand my remarks on this point. It is not of much importance, and common sense demands that little more time be spent on it, but it is interesting to note how touchy are the champions of common sense. If Messrs. Grant, Robinson, and Bedworth will agree that machine design is just common sense, then I will agree that Scientific Management is also just common sense, because Scientific Management is the science of design applied to the management of both men and material.

Why did Taylor take 26 Years for his Experiment?—Mr. Page asks this question. It was like all great experiments. Dr. Taylor says that if he had had the experience before he started that he gained after 26 years, he could have finished this work in a fraction of the time. The experiments were very laborious and much early work was found useless in view of later knowledge. His experience is surely the experience of all life. When we look back it seems as if we might have reached the same stage so very much more easily and quickly.

Criticism of Scientific Management in its Treatment of Labour.

That Scientific Management ignores the workers and their psychology, creates boredom, destroys initiative and makes them automatons, drives them, is inhuman and calls for sacrifices.—The latter part of this heading would make one imagine it was an extract from Sir James G. Frazer's "Golden Bough" relating to human sacrificial rites in the time of our prehistoric ancestors. But words to this effect are used in all seriousness by British engineers in the twentieth century, as applicable to Scientific Management. Mr. Mensforth misrepresents Dr. Taylor by saying that he advocates that the system comes first and the human element second. This is a complete perversion. The present system puts the machine first and the man almost nowhere. The depreciation of buildings and plant is understood because it directly affects capital values, while human depreciation does not show in the balance sheet and is almost entirely ignored under the present system. We have in Mr. Mensforth's criticism the failure to grasp the great fact that the doing of useless work can never improve a man's brain or character. We have the "ox" bogey and the bogey of being responsible to eight men. It is hardly possible to serve even two masters far less eight, but it is very easy to receive instruction from more than eight teachers. Until the old type of manager can eliminate from his mind the present conception of autocratic foremanship he will never be able to understand the vast difference that functional foremanship effects throughout the whole factory organization. Finally we have the "stop-watch" bogey. When the value of time-study is really understood by masters and men, the stop-watch will create the same "atmosphere" in the machine shop that it does in the sick-room when the doctor counts one's pulse. The men have far more common sense about these various bogeys, from which so many of their masters seem so anxious to protect them. Mr. Pilling says it is an "extremely hard paper" and Mr. Allcock speaks of "the danger of de-humanizing industry." How can this be done when it has never yet been humanized? Scientific Management is the first system which definitely sets out to do this very thing—to humanize industry—and it is because I feel so strongly on this point that I advocate its adoption. To humanize industry is the great thing which will justify industrialism from the serious reproaches of the past and make an industrial career worth while,

in a much higher sense than the economic. I deal at length in my paper with all the points under this sub-heading and no new facts are produced to refute my arguments. Scientific Management does not demand "sacrifices" (Mr. Keith). It is not another name for sweating, which exists now and will always be possible under the present state of affairs. Scientific Management makes sweating as impossible as any external control ever will. It does not drive (Mr. Martin) like the present systems. It teaches and leads. If driving is resorted to, then Scientific Management is absent. The worker's psychology is not ignored—it is a very big factor which must be and is taken into account. Instruction and training in standard methods do not necessarily create automatons (Mr. Page and Mr. Ranft), because under Scientific Management the same man is capable of doing a greater and not a less variety of jobs. Anticipated larger pay at the end of the week due to the adoption of payment-by-result, does not create "boredom" (Mr. Paul). Many in this discussion have emphasized the fact, proved by their own experience, that time wages are demoralizing, causing apathy and lack of interest, which has been quickly remedied by paying on a piece-work or bonus system. Scientific Management avails itself of this very important psychological fact, which Mr. Sands seems to deny, while the only deference, under the old order, to the worker's psychology is a bad one, harmful alike to the individual and to the community. It is best summed up in a worker's own words: "I like to think I think even if I don't think." That unfortunately does not apply to the manual worker only. According to Mr. Bedworth, to train the mind to do work in the most efficient manner would be "retarding thought." The great value of a university training to a brain worker is the habit of mental discipline acquired rather than the actual knowledge gained. The craft knowledge of the worker on the other hand is slowly gained not by thought but by long experience of rule-of-thumb methods. Scientific Management uses both original thought to think out the best way, and disciplined habits of mind to execute what has been properly thought out. It gives much greater scope to the thinkers in industry than the present system does. Mental discipline, like moral discipline, does not rob a worker of his "individuality." They both strengthen his character and develop his personality.

A man "benefits physically" under Scientific Management just because if "it is necessary for him to perform a certain operation in a given time" Scientific Management teaches him how to do it with the least effort.

Scientific Management and Unemployment.—The introduction of Scientific Management will have the same tendency as the introduction of labour-saving machinery. It must mean temporary displacement of labour, as pointed out by Mr. Grover, but the national effect is not likely to be serious because it is impossible suddenly to adopt Scientific Management throughout the country. I do not understand how engineers can maintain that increased output means more employment, without pointing out that they are thinking months or even years ahead, because they know very well that the worker is bound to think only days or weeks ahead. The long-distance view in this case, without any qualification, makes the workers feel either that the employers do not know the truth or will not speak the truth. They can understand why lawyer politicians divorced from realities talk in this manner, because they know that almost every politician must be taken at a discount. That is the instinctive knowledge which now forms part of our political tradition. Until employers' statements are such that they can be taken at par value by the workers, it will be difficult to make much progress with Scientific Management or any other thing. The suspicion of the worker is amply justified by history. I agree with Mr. Stavenhagen that the fear of unemployment is a real and genuine one, and I consider that one of the principal charges on every industry should be the liberal maintenance of its own unemployed. I am glad that in this I agree with Mr. Pelling, but not with his "pooling" scheme with which I deal later on. The capitalist class, accustomed and able to wait, must appreciate the workers' fear, and until this has been allayed by effective organization and insurance the workers should not be expected to put forth their best efforts. On the other hand, I would say to Mr. Stavenhagen and to all who wish to raise the status of labour, that to oppose the increase of efficiency in production by opposing the adoption of Scientific Management because of the fear that it will create unemployment is to work in a vicious circle. Little or no progress can result through such action and the workers must continue to suffer. Negative criticism is useless in such a case. Why not accept all that science can give in this direction, on the distinct understanding that full employment or insurance is guaranteed and that the workers get 50 per cent of all the saving effected in cost? If labour would put up a constructive fight on this basis, no employers could withstand it. Public opinion would be overwhelmingly with labour. The present sectional and internecine warfare in industry is not winning public opinion, and the workers and the community are paying a heavy price.

That the Workers resent Scientific Management and that Trade Unions will not tolerate it.—Those who use this argument (Mr. Paul and Mr. Martin) as a reason for not adopting Scientific Management are in a decided minority in this discussion. Opposition, if aroused, is due not so much to Scientific Management as such, but because it is something new and because of the general feeling of suspicion. Average human nature, and especially when in a position of responsibility, is usually opposed to everything new. It is the exceptional man that welcomes a departure from custom. As a matter of fact, the individual worker does not strongly oppose it. Handled properly, he is willing to be shown how to do more and better work with less exertion and for more pay. Mr. Paul's story of the resentment of the men because under such a system as Scientific Management "while their wages are reckoned in tenths of a penny, it costs 2s. 6d. to get a split pin out of the store" is most entertaining, but not practical politics. Mr. Dick's description of the trade-union attitude is most instructive. I hardly agree with him, however, when he says that the individual worker finds himself at present in a "happy position"

financially, so that he is not much concerned with higher production and higher wages. Whatever the returned army man may feel, those who did excessive overtime on munitions during the war do not find that their present weekly pay—with overtime forbidden—is high enough, and the very fact that they have so much more leisure means that they require more and not less money in order to be happy. It is because of this very leisure, which gives a taste of better things to come, that we probably have strikes and demands for more pay, and yet without this leisure, progress towards a higher standard would hardly be possible. Mr. Grover mentions what I have already pointed out in my paper, that the trade unions "dislike competition between man and man in the same shop." This attitude may have been necessary when trade unionism was in its infancy, but the official labour leaders of to-day are paying a heavy price for this teaching of the past. Competition breeds leaders, and syndicalism professes not to believe in leaders of any kind, especially in labour organization, and the "rank and file" movement of to-day against their official leaders finds historical sanction in this tradition of the workshop. If labour is still determined severely to handicap her best men for the sake of the mediocre and the slackers, then the whole body of labour will be compelled by economic circumstances to put forth more labour in the total than would be necessary if the best workers were allowed full freedom to put forth their best efforts. The trade unions and the socialists are not actually against Scientific Management itself. They now believe that it will be necessary under a socialist regime, but they are on the horns of a dilemma. From the industrial bankruptcy of Russia under the dictatorship of the proletariat they now see that habits of efficient work will be essential to success. If, however, the capitalist is allowed to introduce Scientific Management on a national scale without any national control, they see that it will strengthen the capitalists' position. The socialists do now believe in Scientific Management but not under capitalism. I advocate its national adoption, with the Government acting as the trustee for the consumers, in order, by that means, to defeat the possible opposition of organized labour and gain the support of public opinion. I hope Scientific Management will win by showing what a great gain it will be to the nation; and if the nation gains, the employers and the workers must gain also. That is why I introduce socialism into my paper. It is not irrelevant or "antagonistic" to do so, as Mr. Sands seems to think. I believe with many of the speakers that the demand for Scientific Management will eventually come from the workers' side. It is very interesting to see that Sir George Gibb, who has probably had more experience of, and responsibility for, settling labour disputes during the war than any other authority, agrees "it is a great mistake in matters of this sort to be afraid of the working man. Prejudice can only be removed by reason and enlightenment. Workmen should be met not with arguments only, but with arguments and facts." It seems to be the consensus of opinion in this country and in America, of all who are interested in Scientific Management, that the employers have given, and are likely to give, the greatest opposition to its full adoption. I consider that if such a demand does come, the employers will lose unless they are prepared. If the employers initiate the movement individualism will triumph, and we will be saved from the bureaucrat and the bolshevik.

That Scientific Management requires unlimited Unorganized Labour.—Mr. Martin's statement is not correct. Scientific Management will spread by means of organized and not unorganized labour, and a far smaller reservoir of labour will be required than under the present system, because the national organization will be so very much better.

What to do with Non-Suitable Labour?—Mr. Fleming asks this question. Under the present system the unsuitable individual is sooner or later discharged and left to shift for himself, probably repeating the same process in one factory after another, and thereby demoralizing himself and creating a large economic loss. With Scientific Management very much greater care is taken to engage the proper man at the start. If he is not successful in one job he is tried at several, till his capabilities are known, all this being possible with a system using trained instructors. If Scientific Management were national, any man failing to find suitable work in one factory would be found work in another by means of local organizations specially attending to this. If a man were thoroughly and hopelessly incompetent and useless, it would be better to know that man and segregate him and not allow him to roam about as at present, creating nothing but trouble. Nothing could be more haphazard and less scientific than the present method of hiring and employing men in the average workshop of to-day.

Profit Sharing.—The Priestman system of collective bonus as mentioned by Mr. Allcock and Mr. Grover, may be carried out with many of the features of Scientific Management, but Scientific Management does not agree that collective payment-by-result is psychologically sound. It does not reward the worker in proportion to merit, underpaying the best and overpaying the poor workers. It seems mostly applicable to processes or mass production and not to the engineering industry as a whole. This also applies to profit-sharing as described by Mr. Pelling. If good profits are made it will succeed, but if they fall away and disappear, the workers, especially those who may have put forth extra effort, will be keenly disappointed and trouble is likely to result. Such schemes work best in monopoly processes with assured profits, such as soap-making. It is not fair to expect the best workers to be so altruistic as to earn extra profits for the poor ones, and I question if this mixing of altruism and economics is really in the interest of the individual and of the nation. It is like the volunteer system, good for the few volunteers and very bad for the large remainder of slackers. With a premium bonus system under Scientific Management the good worker will always get his reward whether the company makes a loss or not, and the reward is paid weekly. To pay bonuses monthly, six-monthly, or yearly, is to make the worker wait too long. The ideal is to let the worker know what he has made each day if possible.

CRITICISM NOT DIRECTLY CONCERNED WITH LABOUR BUT DIRECTLY WITH THE SUBJECT.

Confusion between Scientific Management and Mass Production.—There seems considerable confusion on this point. The two things are not comparable, not being of the same order, and still some seem to think they are very much akin. Major Pells agrees with what I have just said. Mr. Robinson agrees that Scientific Management is suited to varied output, and Mr. Pearce that it is best suited to such output. Mr. Paul and Mr. Pettifor think of Scientific Management as a synonym for mass production, and Mr. Vines says it is more easily applied to mass production. With mass production it is possible to develop a very rigid system of management, thought out most carefully to the minutest detail, because even the smallest detail repeated tens and hundreds of thousands of times is capable of producing a considerable aggregate gain if performed in the most efficient manner. Scientific Management is almost a *sine qua non* for such production, but it is possible that the relative saving between average inefficient management and Scientific Management as applied to manufacturing companies, not on mass production but on a varied output where a fair quantity of standardized parts is possible, may be even higher, just because with this kind of production it is more difficult to reach high efficiency. Scientific Management can also be applied even in a repair shop, but the details will be very different from those applicable to mass production. Scientific Management should not be confused with any special kind of product, and Mr. Paul's reference to "Fords" and "Rolls Royces" still further confuses the situation. Scientific Management is science applied to the elimination of waste in all directions, and consequently can be applied with gain wherever men work either by hand or by brain. The trained draughtsman of the future will be able to record the necessary standard times on the drawings more quickly than he now arrives at the dimensions and particulars of material. The trained worker will read the instructions just as quickly as he reads the drawings.

Omission of Reference to "Quality" and "Costing."—These, of course, are not new to Scientific Management, and Scientific Management has not anything very original to say about them. Mr. Heaton knows that the tendency of Scientific Management is to improve quality and especially to make it more standard. Payment-by-results, as I have pointed out, is impossible without proper inspection of quality, and without costing. As Major Pells suggests, costing is a detail and a great deal is now said about it, especially by the politicians and the Government, who think that "costing" will save the industrial situation. After all it is a detail, an absolutely essential one it is true, but still a detail. At the best it has not very much life in it. It records what is done, but is not much of a doer itself, and is so liable to abuse, like all historical records. We must have efficient costing just as we must have efficient book-keeping, and the relation of costing to production is very much like the relation of book-keeping to business.

Difficulty of allowing for varying tolerances, etc., under National Scheme (Major Mavor).—This will mean the collection of much data, but with such a system in force as I have outlined, a national standard of quality would soon be established for all classes of work, and this would make possible a great elimination and thus produce a great gain. As an individual employer I agree with Major Mavor that "He travels fastest who travels alone," but as a member of the British engineering industry who wishes that industry to lead the world, I do not agree. The progress of individuals will be far too slow in the aggregate for the nation. Such individual progress is unscientific if considered on a national scale, as it means such a great duplication of the same trial-and-error process in a multitude of shops. We are so conservative and close that if we discover a good thing we tend to keep it to ourselves. That does not seem to be in the national interest. Of course the object of this paper is to create a "bias" in favour of Scientific Management. Until that bias is created, any such national scheme as I have outlined is impossible.

Supply of Materials.—Mr. Parsons has somewhat misunderstood my remarks regarding all mechanisms being of "secondary importance." He describes and gives an illustration (Fig. A) of a very interesting graphical method of recording the progress of manufacture of a large machine from "date of order received" to "date of plant delivered." Mr. Parsons assumes that the employers have the proper mental attitude towards the men, and if this is granted then all such schemes as he has described become of primary importance. His scheme, however, deals with the handling of material and, as already pointed out, the object of this paper is to deal with labour, and as far as labour is concerned it is worse than useless to adopt the various "mechanisms" of workshop and office as developed and used under Scientific Management if this proper mental attitude does not first exist. A change of both heart and head is necessary for the successful handling of labour. The correct mental attitude of the employer to his men is thus of primary importance, after which motion and time study become possible, consequently the latter are secondary both in order and value. Mr. Bedworth says: "What good will it do to have an elaborate system of feed and speed if we have not the material to feed our machines?" Of course it is no good, and science must be applied to the handling of material as well as labour. Dr. Taylor went fully into this, but the problem of material is an old story and the application of science to its solution is agreed upon by everyone as most desirable. It seems to be the failure to distinguish between system as applied to material, and science as applied to labour, that makes the opponents of Scientific Management so annoyed at its claim to be original. It makes little claim to originality regarding material, but of course without materials it is impossible for labour to be efficient, and there is little doubt that a considerable part of the so-called restriction of output at the present time is due to the abnormal shortage of certain classes of essential material, for example, steel plates for shipbuilding and insulated copper wire for electrical machines. I regret I cannot give Mr. Parsons any further details regarding the

government report of the adoption of Scientific Management in a foundry. Considering, however, that the output was simple and on a mass-production basis, the supply of material in this case would be easily accomplished and one would imagine that almost all the saving would be effected by the efficient training of labour. In building an intricate machine, however, the supply of the material at the right time may be of greater importance than an increase in the efficiency of labour by means of motion and time study. In such a case Scientific Management would pay the greatest attention to material. Does it never strike the champions of the present systems that the scramble for material is unscientific and a national loss? Is it not time to have industry develop a general staff to deal with the supply of both material and labour? Industry should now be past the stage where individual firms have to fight for the necessaries of industrial existence. The struggle and the "survival of the fittest" ought to be raised to the higher level of efficient production. We want a Quartermaster-General and an Army Service Corps for industry. Our present methods of getting material and labour are on a par with the foraging methods of Napoleonic days. We do not want the Government bureaucrat, but national control did accomplish things in spite of the bureaucrats. We want a centralized control initiated, organized and run by industry itself in the interest not of great monopolies or amalgamations but of all the producers. Consider the present situation in shipbuilding. The shipping companies want ships which they cannot get fast enough, because shipbuilders are short of steel plates for which the steel makers require pig iron, which again requires imported ore, and this is not being imported because we are not exporting enough coal. Because of the lack of outward freights to ore-producing countries, there is a scarcity of ships coming to this country with ore. The shipping magnates want ships but apparently do not consider it their job to divert any ships for the purpose of carrying ore. They seem to prefer to earn higher freights in other directions, meantime retardation of output is produced in all these other very important trades. It is such lack of leadership in high places or such indifference to the greater national interest apart from the immediate sectional gain that creates State socialists. Many State socialists hate the bureaucrat and admit his great capacity for blocking progress, but in spite of that they think the bureaucrat a lesser national evil than the capitalist intent on immediate gains, no matter how other sections of the nation may suffer. The great amalgamations of shipbuilding, steel, coal and engineering are attempts to solve this problem, but it may not be a solution in the national interest. It may become a fight between giants, and the rest may go to the wall, and then we may have individualism at its worst, which is bound to produce the natural sequence—State socialism. When the small and the large firms co-operate together through a centralized organization, then we shall be able to preserve the maximum of individual initiative in actual production along with all the advantages of the fullest co-operation. That is how science might attempt to solve the problem on a national basis.

Criticism of my Opinions Indirectly Connected with the Subject.

That Factories in the country should pay lower wages.—If country factories are so difficult and costly to run (Mr. Pettifor and Mr. Vines) why are they built? There must be some compensation in addition to the cheaper ground rent, because that in itself is not sufficient. If this difficulty of inferior labour actually exists now, it surely did not always exist, and it must be a sign of the times that the best workers, whether manual or brain workers, are no longer content to be marooned in a country district however beautiful, where it is impossible to find that stimulation to the mental and spiritual side of life so essential under our present civilization. The concentration of industry in densely populated cities is of course not in the best national interest, but it is questionable if it is desirable for industrial workers to live in rural surroundings entirely away from what the city can give. The ideal conditions seem to be in free open spaces, outside the larger towns, and of course in such cases the supply of efficient labour is not difficult. The tendency of industrial progress will be towards less heavy muscular work, which will be done by machines. Nervous energy will tend to replace brute force, and such workers will require more intellectual recreation and entertainment than in the past. It is difficult to see how this can be obtained all over the country, and if the electrical engineer solves it by cheap and rapid transit, then he will also solve the labour difficulty as well. This is a very small country and the geographical differences in the cost of living (Mr. Stubbs) are more often due to different standards than to different prices. The ideal should be to raise all to the highest standard and therefore I do not think that lower wages in the country are in the national interest, as this tends to keep the general wage level down.

That Labour is a Commodity—subject to Supply and Demand. Economists are almost as dogmatic as theologians. The enthusiasts, or are they the cynics, argue that economics is the driving force of the world, the vital force of civilization, the real motive power behind all wars and even great religious movements. The myth of the economic man still enjoys world-wide credence. The followers of Karl Marx have forced the materialistic conception of history to the fore, and have thus strengthened the sub-conscious reactions of orthodox economists so that they can hardly conceive of a future state of civilization in which economics will take a very second place. They seem to think the present state of affairs is so perfect and absolute, having lasted throughout civilization, that they cannot see any alternative. When economic wealth is abundant everywhere then labour will cease to be a commodity to be bargained about. Very little labour will be required of each individual, and that little will be willingly offered to the community. That is a Utopia doubtless, but the tendency of Scientific Management is towards that Utopia, and the smallness of the apparent progress should not unduly worry us, so long as we know that we are on the right road. Before trade unions existed, employers bargained with individual workers. Labour organization is now recognized by all British employers,

so that they bargain with the individual no longer. With the national adoption of Scientific Management a vast number of details over which bargaining now takes place will be eliminated, and eventually the issue will be narrowed down to one point—the national standard rate. As civilization advances it will not always be a question of force getting the best of the bargain. Ethical considerations will gradually dominate, founded on economic qualifications it is true, but force will not be used—not even potentially. When force no longer predominates, as it no longer does in the best relations between husband and wife, father and son, then economic truth will become a blessing to all, and not as at present be used by the stronger as a weapon to bewilder the weak. As a concrete example of what I mean, consider the recent case of the railway porters, and the inquiry into the conditions of life of the dock labourers. A strong appeal is made to the humanitarian side of public opinion in order to gain sympathy and support for the argument that a minimum wage should be based on a certain standard of living, irrespective of any standard of work done. The ethical appeal to a higher sentiment is good, while the ignoring of economic conditions is bad and confuses the whole issue. Civilization, especially after the war, cannot afford so many railway porters lounging about a passenger station in order to maintain the dignity of passengers able to carry their own bags. Such men are not worth £2 a week to the community. I question if they are worth 10s. Neither the unions, the employers, nor the Government have the courage to say so. No one seems to think that the problem could be solved by the installation of a proper and efficient system of handling railway passengers' baggage, instead of maintaining a system inherited from and only suitable for the days of stage-coaches. Do away with these porters and put them to do more valuable work. If such work cannot be found right away, pay them liberal insurance. Let us see how inefficient we are and so get rid of the inefficiencies the quicker. At present they are all lost sight of. Humanitarianism which ignores economics in this fashion, does harm and not good. It is a reaction from the bad past in which economics ignored humanity. It is of great interest to note, as a partial step in the right direction, the very recent ruling of the Industrial Court that the cost of living will not be taken into account in future when fixing wages, but that "the remuneration of the work-people should now depend on the value of the work done." If this were all it would be partly satisfactory, but a definition is added which practically damns the whole thing, namely—"the value of the work done depends on the state of the market." Here is the same old merchant idea, now so anti-social. It is as vicious as the Excess Profits Duty which encourages and stimulates the maximum of profiteering. Because the cotton magnates, for example, have raised the price of cotton abnormally high it will be correct apparently for the Industrial Court to accept the latest demand and award abnormally high wages to the cotton workers so that they also may be profiteers. Of course the other workers in trades which fail to boost prices to such an extent will calmly and peaceably accept such a state of affairs. It is again another glaring proof that the scientific mind does not direct or control us. Scientific Management makes humanitarianism on an economic foundation possible, and with scientific investigation of effort required and work done, a scientific and humane basis of "value" will be possible. The present confusion of thought puts science and lasting progress at a discount and places a premium on force backed by sentimentality and *laissez-faire* economics. Science has nothing whatever to do with bargaining, and as production becomes more and more scientific, force and bargaining will gradually be displaced by truth.

That Scientific Management as evolved in America will not do in this country.—I hold no brief for America, and I yield to none in my feeling for this country. Just because I am out-and-out British, the idea of qualifying Scientific Management by the word British in order to distinguish it from its American brother, or rather father, is to me most repugnant. The basic principles of analysis and measurement which underlie Scientific Management are not national but universal. The details may vary in all countries, in fact, must vary if Scientific Management be properly applied, because national conditions and psychology vary so much. To add a qualifying word to a basic title in order to indicate difference of detail seems to me to limit the title, and Scientific Management must have the broadest possible title because it stands for the broadest possible conception of management.

I thus do not understand Mr. Stelling's over-emphasis of "British Scientific Management." Mr. Pearce also thinks that "We should develop a school of thought in management which is typically British." The two great English-speaking democracies must come closer together in the interests of the world. There must be greater appreciation of each other, and this kind of national bias and criticism is the very thing that causes us to get further apart. Some believe that the lack of tact on the part of American exponents of Scientific Management has spoiled a good thing, but surely this is not the way to prove our capacity for tact. The American engineers, with Dr. Taylor at their head, and after long and bitter discouragement, have made this question a very live one to-day. The few British firms that have adopted it in part prefer to keep quiet about it, and regard it more in the nature of a trade secret. Secrecy in management should be as much out-of-fashion as secrecy in diplomacy. Also I do not quite see why Mr. Stelling should expect me to give a paper from his point of view. The representation of Scientific Management is not a repetition job. There are endless ways of presenting it and I have done it in my own way and am very glad he has apparently an entirely different way. In view of what I have already said in this reply, it is hardly necessary to explain again why I have not mentioned British experts. There was never any intention on my part to slight or depreciate their work. This disinclination to recognize that any good thing can come out of America or in fact out of any other country—except perhaps Germany in pre-war days—is a dangerous mental attitude to encourage. Let us learn everything we possibly can from America, and while we delete what is bad for us, let us be glad

and not grudging of the good. We are a big people, let us act with dignity and not as a petty little country.

Criticism of my Scheme of National Committees.

Mr. S. Mavor misunderstands me, because I certainly do not advocate that Scientific Management should be imposed on us by the Government. What I believe is that the employers' federation and the trade unions must first agree about it and then go to the Government to have it legalized. I cannot do better than quote Mr. Paton at Manchester—" When an economic truth is established in industry its value should not be left to voluntary acceptance by a community incompetent to appreciate it." The consumer's interests must be protected as well as the producer, and this would be the chief function of the Government. Without this protection we would approach very close to the dictatorship of the producers, namely the " syndicalist " or the " Soviet " systems, in which the powerful industries —if masters and men agreed—could dominate the country and even the present semblance of democracy would disappear. I agree these are only tendencies, but in industrial and political movements tendencies are all important. Few have discussed this question of national committees. It is evident the political aspect does not arouse the greatest interest, which is easily understood but is regrettable. Until engineers and scientific men do take an interest in politics, the politician will continue to be very unscientific. Mr. Mensforth dismisses my scheme and considers we have already arrived at just such a stage. Mr. Paul and Mr. S. Mavor do not think it advisable in the meantime, and Messrs. Bunting, Huntley, Soper, and Major Pells seem to think that I advocate progress from the top downwards. They say it must start in the individual shops. Now my idea of the national committees is that they are equivalent to standardization committees and will deal with the lowest common denominator of all the problems in all the individual shops. Unless this is done it is impossible to arrive at any national standards and each individual firm will require to do almost the same work as other firms. No national rate-fixing would be possible, in fact no national organization would be possible. The territorial committees simply examine the national standards and create district factors where necessary. The shop committees do the same for each shop. The national committees would investigate, experiment and initiate standards. They would do most of the research in laboratories and specially selected works, as Mr. Soper points out. The other committees would be principally concerned with the application of these standards. It is impossible for the individual firms to do the necessary research, and even if they had the means it would be most extravagant. The application of Scientific Management on a national scale must be on scientific principles. The two functions of research and application are clearly pointed out by Major Pells and still he thinks I am wrong. Dr. Taylor told me he believed a centralized Government Department would eventually do the research and create the standards. The application, of course, can only be done by the individual firms. I think there would be less confusion if we did not talk of " up " and " down," conceiving thereby a pyramid with the Government at the apex and the firms at the base. Think of all in one plane, with the Government at the centre and the workshops at the circumference. The conception of centrifugal rather than centripetal progress seems the more understandable.

Employers' Federation and Labour Questions.—A good suggestion is made by Major Richardson regarding the possibility of the British Electrical and Allied Manufacturers' Association extending its activities and tackling the problem of workshop methods. Mr. Atkinson also suggests that this Institution and similar institutions and the Joint Industrial Councils could do good work in this direction. I have little doubt that as far as the electrical industry is concerned, the B.E.A.M.A. could do valuable work in this important field, but unfortunately the Engineering Employers' Federation is so jealous of what it claims is its very special preserve, namely everything affecting labour, that it will not tolerate any modern rivals such as the B.E.A.M.A., the British Engineers' Association, or even the great Federation of British Industries, whose statesmanlike proposals on unemployment it easily managed to stifle and render abortive a year or two ago. Unfortunately in the council chambers of the employers we still have too many men who belong to the old school, men who are still imbued with the warring instinct and still believe in strikes and lock-outs. The rising generation of employers will almost all know what real war is, and they have had enough of it. They have a broader outlook, but these younger men do not have enough say in any of these most vital problems, and their keener vision and better feelings have much less scope than is in the national interest. The organization of national district and shop committees proposed in this paper is practically identical with that of the Whitley scheme, but I do not see how the same committees could do this work. The Whitley committees are not necessarily expert but composed of men of general experience and knowledge. Committees on Scientific Management must be expert in engineering practice and industrial fatigue. Such committees could co-operate with and be affiliated to these general committees. Being expert, the members would have to be carefully selected by the employers' federation and the trade unions, and any further selection by the voting of all employers and employees would require to be simply a choice of two or more experts. Mr. Carter points out that the technical and management staffs have been entirely overlooked in the Whitley scheme. This is what we would expect from the birth of this scheme, but this serious defect is fully realized and Mr. Whitley hopes it may be put right in the near future. Without question the staff is in a very favourable position to act as liaison officer between capital and labour, and it has a great opportunity to gain both the power and prestige which it should possess but which up to now it has never enjoyed.

Wider Education Necessary.—I agree with Mr. Hannay that I have rather neglected the question of education. I did not forget it at the time, but I was concerned at increasing the length of my paper. I now see I should not have omitted it because it is one

of the most important factors governing the situation. Scientific Management requires special teachers and colleges for the training of expert staff officers and of the capitalist employers themselves. As pointed out by Mr. J. Richardson we have at present very few of such men, and a movement for specialization in this field has only just started. Manchester University is to be congratulated on having tackled the matter thoroughly. Glasgow University has now a lectureship in Engineering Production as pointed out by Major Nicholson. That of course is not enough but it is always a beginning. As universities do not advertise very much, I am not aware of what is being done in London and by the other universities. England is probably the greatest worshipper of tradition in all the world. It still dominates her great public schools and universities, her law courts, her politics and her church. Science has fought hard for a foothold but has not yet won it. We are worshippers of the dead just like the Chinese, but we do not know it. We are still ruled by the dead hand and the dead ideals of civilizations inferior to our own in science and social ethics. Science has within very recent times placed the whole world at our feet and we are blind and dull and our attitude towards it is very like that of the man with the muck-rake. Our schools and colleges are starved of money for scientific laboratories, teachers and research, because politicians, public men, and public opinion are unscientific and the church anti-scientific. Research is the very life of science. There are two distinct branches, and one is now being tackled by the Government in co-operation with industry. It is the utilitarian branch, namely research along certain definite lines in order to improve and cheapen production. It seems right that industry itself should carry out this work, but such research alone is not enough and will never carry us where we can go if we have the will. The higher research is not concerned with production or industry but solely with discoverng more truth and broadening the field of knowledge, without which progress in entirely new and unknown directions is hardly possible. This requires scientific genius and much money for experiments, which are so often a groping in the dark, redeemed at long intervals and after much toil and expense, by a great discovery. Few commercially-minded public men thinking of dividends and few Governments thinking of taxes and votes can possibly have the scientific attitude and vision to see the necessity of spending money for heaven only knows what. We are such a short-range practical people that we seem to have no means of grasping the possible value of anything yet unknown. Unlike the Greeks we pay no homage to an unknown God. Scientific Management demands new ideals concerning industry and labour, and consequently it is much easier to start with the young, who have less old ideas to be eradicated, before progress can be made. Scientific Management requires a new mental or internal attitude, and it is the endeavour to graft a kind of new external system on to these old innate conceptions that has caused so much trouble in America. The new idea must go right down to the furthest roots. Because Scientific Management has been so slandered and misrepresented, due to misapplication, it has naturally not attracted enough of the best attention so as to demand proper education. If we can create a better atmosphere which will make it possible for the majority to realize that there is something true and consequently good in Scientific Management, then there will arise a demand for education which will cause things to happen. All this of course refers mostly to the management staff. Regarding the workers, it seems the wise thing to do, as pointed out by Mr. Booker, to make a start meantime with the apprentices. Classes must also be started for them in evening schools and technical colleges, but much can be done in the works. In large works where there are schools for apprentices, much can be done by the cinematograph to teach quickly the proper positions and methods of working, and progress of individuals can be quickly checked and corrected by means of these instruments already developed, and records of which I have given in my paper. The teaching and instruction must not be by rule-of-thumb but by scientific methods. The problem of efficient rate-fixing is a very difficult one because we must continue to use the present rate-fixers trained under rule-of-thumb methods. Much that is now called rate-fixing is just more or less guess-work. There is a sporting chance between masters and men of getting the better of one another. It seems acceptable to both, and on the whole workable, as both sides seem to come out about even in the end. It is demoralizing to masters and men to fix rates in this manner, and it is useless to expect enough capable rate-fixers until rate-fixing is recognized as a science, and Scientific Management is the only system of management that does that.

Because Scientific Management recognizes that rate-fixing is a science rather than an art and therefore sets about fixing rates in a scientific manner, there is not the same chance of making serious miscalculations as so often happens with the present system of guessing. If the men consider the times allowed are too short, the matter is quickly adjusted by referring to the elementary time analysis. This usually convinces the man, but if there is an error against the men it must be rectified, while if it is against the employer it must remain. Mr. Ranft objects to my use of the word "easy" in connection with such disputes, but I still claim that Scientific Management provides a very easy solution of all such troubles, as compared with other unscientific systems of rate-fixing. It is an interesting psychological fact that when workers are asked to estimate elemental times, they invariably underestimate them, while claiming the total time to be too short. As an instance, 3,000 hours were allowed for a job in a shipyard and the men demanded 5,000 hours. The job was examined in detail with the men, who were asked to give their times for the various elements of the job. The sum of the times given by the men totalled 1,700 hours as against their claim of 5,000 guessed for the total. The time allowed of 3,000 hours was based on average men doing the job in 2,000 hours and thus earning 25 per cent bonus on their previous wages.

I would also point out that the medical profession have still to be trained in the special field of industrial pathology and hygiene, including psychology, and that

all public men, including especially politicans, should have to know something of economics and sociology. That we are moving quickly in this direction is proven by the proposed establishment of a National Institute of Psychology. To quote Dr. Myers of Cambridge, "It will determine in individual factories and offices the best methods of reducing fatigue and monotony, of selecting workers for the occupations for which they are mentally and physically best fitted, and of distributing the hours of work and rest; it will provide training courses in industrial psychology and physiology, study the psychological relations between management and labour, and spread the general results of its work." In addition to this special vocational education we of course require a much broader general education, especially for the workers, and taught in a scientific manner, otherwise increased leisure will not mean higher standards but will only produce idleness. This state of affairs seems somewhat of a vicious circle, but I believe the nation must take the risk of giving the opportunity first before the workers are fully ready to make good use of it. If this opportunity of higher wages and more leisure is withheld until the workers have been educated to make good use of it, then it is likely to come too slowly, because without means and time for education—which should include travel as well as book learning—little higher education is possible. We must therefore put our faith and our money on the rising generation and be prepared to let the present generation waste and misspend their extra time and money if they feel inclined that way. As the late Benjamin Kidd argues, we have the capacity to take on an entirely new social orientation in one generation if we only will it. Without such faith, the rising generation is always penalized because of the fear that the present generation will misbehave. As we are ruled by the older generation, they I suppose know how bad they have been and are capable of being, but the younger people do not take kindly at all to this old idea of innate badness. The war has proved that young human nature is something finer than their elders were willing to admit.

Machine-Tool Makers and Scientific Management.—A very good suggestion is made by Mr. Robinson, that machine-tool makers should consider it their duty to supply proper time-study data with their machines. With the national adoption of Scientific Management much investigation would be carried out in co-operation with the machine-tool makers. There is no question that it would still further improve and standardize machine-tool design. Dr. Taylor was instrumental in effecting many improvements in machines, not to speak of his epoch-making discovery of high-speed steel.

The Psychology of the Attitude Towards Scientific Management.

As the whole situation regarding Scientific Management is psychologically interesting, and as my plea is that we are near the psychological moment when Scientific Management can be adopted on a national scale in this country, it seems to be relevant briefly to put on record my opinions regarding the reception of this paper, as it may form a fairly representative diagnosis of the attitude of engineers throughout this country to this subject at the present date. I will give my opinions in the order I formed them. In Glasgow we have had good papers on the subject and several discussions, and there is little question that most of the younger generation and many of the older are thoroughly interested. In pre-war days the mention of it at an engineering meeting produced no interest or discussion—only scorn. In London the reception was decidedly mixed, as one would expect, due to the greater diversity of critics both as regards years and training, and there was not enough time for all who wished to speak. In Manchester much of the criticism was of the scornful order, and if Manchester is representative of Lancashire, there is little doubt that the greatest manufacturing district in the world still sticks to the same kind of economic gun as that designed in 1846. I do not believe, however, that the majority of the meeting backed up the critics. Some of the younger men told me they were all with me, but the discussion having started off very anti, practically maintained itself so. The first few speakers are very important and the rest often seem to follow more or less the same lead, and those who would like to champion the opposite view seem to lose courage. So few men like being in a minority, and especially one publicly exposed. In Birmingham, where they have probably heard more about Scientific Management, the attitude was serious and interested. The Birmingham engineers were keen and anxious to get at the truth. At Newcastle the attitude was much like Glasgow. Excluding London, which we will consider as neutral—equally for and against—although I feel that the majority were really for Scientific Management, out of the four largest provincial engineering cities three were decidedly in favour of further progress along the lines of Scientific Management, and the fourth will be when the younger men have the courage to tackle the 1846 *laissez-faire* gentlemen. Mr. Carter seems to think that such public meetings are likely to produce less results than quiet talks to individuals. That "a strong impression on a few minds would be very much more important . . . than a weak opinion on a larger number." I entirely agree with this last sentence, but the problem of creating a "strong impression" is often much more difficult with a few people than with a larger audience. Enthusiasm is more easily produced in a crowd, and by that means the few minds in the crowd may be more strongly impressed than if they were tackled individually. Again, some speakers find it more easy to speak enthusiastically to a large number because it is less personal and the numbers produce greater mental stimulation. The mental and emotional action and reaction is on a larger scale. We must surely carry on propaganda by both methods, but my contention is that if we leave all the public speaking to lawyers and politicians it will be quite impossible to create a public opinion in favour of science as opposed to mere tradition. In conclusion, I would ask for lenient consideration if I have overlooked any suggestion made or ignored any point raised, because any such omission is not intentional. I should also like to say to those who differ from me that as they hit hard, so I hit back in reply, but I much prefer hard hitting to apathy and indifference.

WIRELESS TELEPHONY ON AEROPLANES.

By Major C. E. PRINCE, O.B.E.

(*Paper received* 17 *January, and read at a* WIRELESS SECTIONAL MEETING OF THE INSTITUTION, 18 *February*, 1920.)

Wireless telephony in aeroplanes having been born in the Great War, and having been developed under that terrific stimulus, it is hard to approach the subject except from this standpoint, or to avoid the historical method of treating it. It is impossible in this paper to make more than a very brief survey of a large subject, but the author trusts that it may be of interest to give some account of its genesis, and of how the technical difficulties were met and conquered.

The subject of wireless telephony is in itself a combination of two others, namely, telephony as understood in ordinary line working, and wireless telegraphy with its group of associated problems. The present paper will treat both of these as well understood, and will be confined mainly to the special application of wireless telephony to aircraft, with which the author was so closely associated.

After the outbreak of war, while carrying on experiments at Brooklands, mainly with a view to producing a continuous-wave valve transmitter sufficiently simple and practical to be used in the air by unskilled personnel, the author was struck by the great advantage which would be gained by the use of articulate speech instead of Morse, if it were possible, for artillery observation and reconnaissance. It was obvious that a fleeting target would be more quickly indicated, or a location described by word of mouth, than by a system of slow and laborious telegraphy and map references.

A skeleton set was made up and tried in the air, and at the first attempt some approximation to intelligible speech was received.

This was in the summer of 1915, and it is believed to be the very first occasion in the world when wireless speech was received from an aeroplane.

In spite of this initial success, the difficulties in the way of producing good articulation, and a light and practical set, appeared to be almost insuperable; but they were gradually surmounted, and to-day good telephony is possible not only from air to ground, but from ground to air, and—most difficult problem of all—from machine to machine.

At that period the soft valve was in use, with a lime-coated platinum filament, and the handling of this by unskilled persons was one of the greatest difficulties. Except for this the purely electrical difficulties have throughout been far less serious than the telephonic, practical, and mechanical ones.

In the first place the transmitter must work in a region of intense noise, vibration, and often violent air disturbances, in which even the real human voice is unable to speak to the human ear over a greater distance than a very few inches; in which the velocities of the air currents are alone enough to cause distortion, and the very muscles of the face can hardly retain their true shape under the varying wind pressures.

When it is remembered that under these extreme conditions speech has to be converted into current modulations, these modulations radiated, received, rectified, magnified, reconverted into sound, and again heard by a human ear set amid a similar uproar, the final achievement of inter-machine telephony will be appreciated.

In the early stages the difficulties of reception of speech in the air were so great that only transmission from air to ground was attempted, and the first practical set evolved was a transmitter, capable of employing either speech, continuous wave, or interrupted continuous wave (subsequently called "tonic train").

The circuits employed are shown in Fig. 1.

It will be seen that it was essentially a self-contained oscillating system, to which the aerial was loosely coupled. The microphone was inserted in the earth-lead, and modulated the radiation by varying the resistance of the aerial. The valve was not in view, but the set was provided with three meters, A showing the aerial, *a* the filament, and M A the high-tension feed currents; the readings of which gave all the information necessary to make the adjustments. The plug (P) served to bring into action either the microphone (M), buzzer (B), or to complete the circuit of the artificial aerial (A A). If not plugged in, the set worked as a plain, continuous wave-transmitter. The key was mounted on the top of the set, which was suspended by a three-point rubber suspension. High-tension current was supplied at 600 volts from a dry battery of small cells, weighing about 36 lb., made up in a flat form and usually carried under the footboards.

The microphone used was selected from a variety of ground types and, originally, was suspended on rubber in a frame held in the hand.

Some of the best ground microphones proved useless in the air, and the choice finally rested on an old-type Hunnings Cone. It is interesting to note that it is almost impossible to predict from its behaviour on the ground whether any particular microphone or type of microphone will work satisfactorily in an aeroplane; and in the Royal Air Force every individual instrument was tested actually in the air.

The set above described weighed, without batteries, 10 lb. It was used on a trailing aerial 250 feet long and employed a wave-length of approximately 300 metres, not very far removed from the natural wave-length of the aerial. In consequence, the radiation was very good. On one occasion when the author was giving a demonstration before the late Lord Kitchener at St. Omer in February 1916, the spoken messages were

picked up and recorded by the Lowestoft interception station at a distance of over 100 miles, although the aerial current in the transmitting aerial was less than 0·25 ampere.

The author was admirably assisted in the production of this set by Lieutenant (now Captain) McDougald, R.A.F.; and, remembering that it was the first practical aeroplane telephone ever produced, and in the alternative use of various types of transmission it anticipated the latest international regulations, he cannot dissemble a feeling of satisfaction that the British Royal Flying Corps was the pioneer in a subject which has subsequently become of international importance.

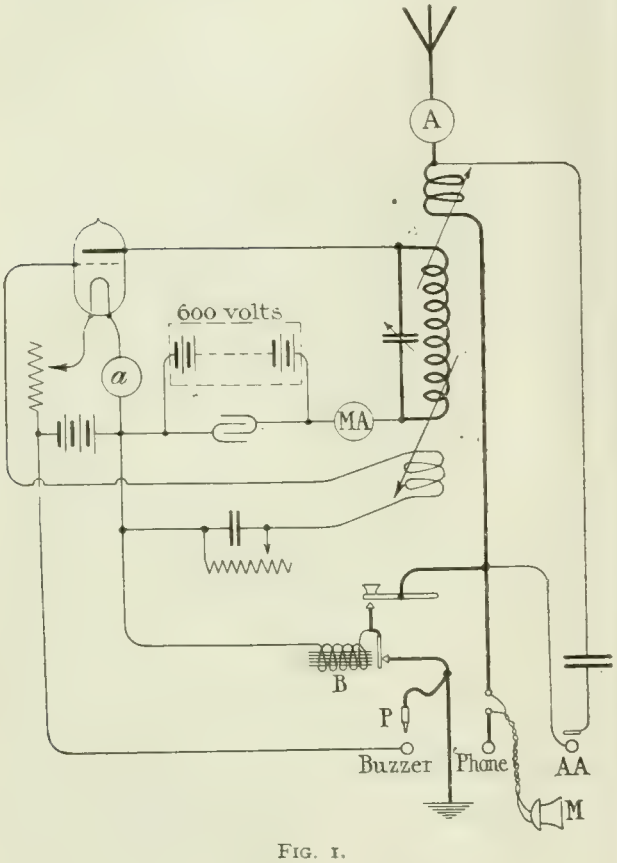

FIG. 1.

This transmission was at first received on the ground on a Marconi double magnification-circuit in which a single soft valve was employed for both high-frequency and low-frequency magnification, a carborundum crystal being used for rectification. Reaction was used to the utmost, and great sensitiveness was obtained. The ordinary working limit of range from air to ground was about 20 miles for telephony, 30 to 35 for tonic train, and about double this distance for pure continuous-wave.

At this time, although experiments in telephony were continually proceeding, it was thought that, in view of the difficulty of receiving speech in the air, it would prove most practical for immediate requirements to transmit to the air by Morse only, and, to this end, the author made up a valve receiver with one soft valve, with practically similar circuits to the ground set. This was tested in the autumn of 1916, and ranges of from 30 to 50 miles were obtained from a ½ kw. spark set It was, as a matter of fact, on this receiver that intelligible speech was first heard in the air and the idea of "remote control" originated. Its adjustments proved, however, rather difficult for unskilled personnel.

The overseas Forces, nevertheless, did not for a long time make any use of air-to-ground telephony, although just before the Armistice a meeting of the Higher Commands recommended its introduction for reconnaissance and similar work, as originally suggested in 1915.

An urgent demand arose, however, for telephonic communications between machines in the air, and all energies were devoted to solving this far more difficult problem.

In considering the application of wireless to aircraft it is important to remember that, besides working under difficult conditions, it was necessarily operated either by quite unskilled personnel, or by those who could only receive a very slight training. It was this, also, that favoured—nay even made essential—telephony as against telegraphy. The average pilot or observer could not have sufficient acquaintance with Morse to read it subconsciously, nor had he the time or inclination for it amid the multifarious calls on his attention while flying. Thus, although it would have been far easier to equip him with Morse communication, it was practically useless. For various reasons, also, there was for a long time no demand for both-way working, and a machine was equipped either for transmission (for the leader to give orders), or reception (for his formation to receive them).

For similar reasons it was necessary to eliminate all possible adjustments; and to show to what extent this was successfully achieved, it may be briefly stated that the transmitting apparatus had none, and the receiving apparatus only two, one of which was seldom touched.

As always, easy working implied difficult designing, and it may be interesting to trace a few of the steps that led up to the chosen methods.

The problem was rendered easier, because by this time the general advance had provided us with a reliable, small, hard transmitting valve of French type, capable of handling about 20 watts, and similar valves with slightly more open grid for use in reception.

Dealing first with the transmitting apparatus, an ordinary reaction or regenerative circuit provided the radio power; and the only electrical difficulty was the choice of the best method out of the many alternatives of applying the voice modulations.

The coupled-circuit system already described, although giving very perfect results for small power, was ruled out on account of the coupling and tuning adjustments and its output limitations.

The following simpler circuit, devised by the author, was also abandoned, but as it is not uninteresting it may be worth describing.

In this, a condenser of about 0·05 mfd. capacity was placed in the earth lead of a simple oscillator. Its insertion or short-circuiting produced little difference in the aerial current; but if a microphone was connected

across it, the loss of energy in this was equivalent to an alteration in the total resistance of the aerial, and by choosing suitable constants and adjustments good variation could be obtained and " breaking " avoided. It has a critical reaction adjustment, and also tends rather seriously to change the wave-length as well as the intensity of the radiation, so that it can give good or bad speech according to the adjustment of the receiver, for reasons about to be described.

In comparing different means of modulation, in every known method (as far as the author is aware) variations of intensity or output are always accompanied by some change of wave-length, and the receiver can be adapted to take advantage of one or the other factor, so that, strictly speaking, any type of transmission should be considered in relation to its reception. Thus, for instance, a receiver in which reaction is relied on, with a very steep and peaky resonance curve, is peculiarly sensitive to wave-length changes ; whereas the modern type of flatly tuned high-frequency amplification receiver, *ipso facto*, takes no account of this, but responds alone to changes of amplitude or intensity.

In practice both factors can be laid under contribution at the receiving end, though probably the ideal method of modulation would change intensity only.

In any system in which the change of wave-length preponderates, good or bad articulation can actually be produced on a reaction receiver according to the slope of the resonance curve on which the adjustment is made.

When, in any receiver, reaction is pushed to the utmost short of oscillation, the resonance curve becomes amazingly steep and the sensitiveness very great, and most remarkable effects can be obtained if the tuning be then adjusted very finely. It is unnecessary, as in self-heterodyne, to detune ; and so full advantage can be taken, by this critical condition, of any change of wave-length, which probably accounts for many of the freak ranges accomplished by this type of apparatus. It is easily seen that a very slight change of wave-length will produce enormous variations of intensity in the receiver, but it is equally obvious that there must be considerable distortion of speech quality, since the true proportionality is lost.

To return, after this digression, to our point of departure, no method of controlling the radiation directly by the microphone proved free from grave disadvantages, and the choice therefore fell on some form of indirect control, of which the most obvious was the placing of a microphone transformer in the grid of the oscillating valve. This, though giving very good results, was abandoned in favour of the final arrangement about to be described and now generally known as " choke control," in which the modulation is applied to the anode circuit of the control valve.

The principle of this system may be made most clear by approaching it step by step.

Let us suppose that in the anode feed circuit of a simple valve oscillator is placed the secondary winding of an ordinary step-up transformer, the primary of which is a microphone and battery circuit (Fig. 2). The variations produced by the voice will give rise to changes

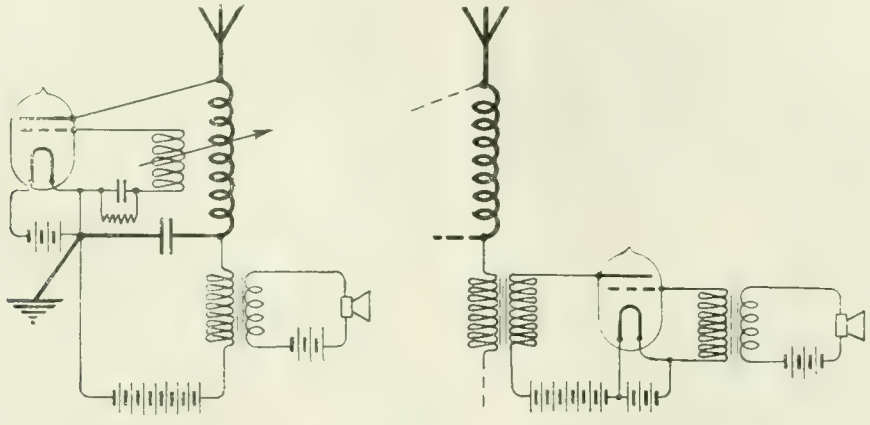

Fig. 2.

of potential in the anode feed circuit, which will be equivalent to supplying the oscillating valve with more or less high tension, and will alter the radiation in a sympathetic manner. Since, however, the energy dealt with will be weak compared with the main supply, success will be only partial. For magnifying this effect let us now introduce another or " control " valve whose grid is acted on by the original microphone transformer, and whose anode is in series with a one-to-one transformer in place of the original one. If the two valves are comparable and supplied with similar high tension, we are now able to apply a modulation or variation of the same order as the energy dealt with by the first or " power " valve.

From this point some easy steps will take us to the actual circuit employed. The control valve can be supplied from the same source of high tension as the power valve ; the transformer can become a choke coil (which is, in effect, a one-to-one transformer), and it is an obvious arrangement to work the filaments and the microphone primary circuit off the same low-tension battery.

The circuit now becomes as shown in Fig. 3, in which P is the power and C the control valve, L is the choke coil, and T the microphone transformer. H T is the source of high-tension supply, and F is the filament battery.

It will be seen that the anodes of both valves draw their high-tension d.c. supply through the choke winding, and as long as the microphone is quiescent, the output and general behaviour do not differ from that of the power circuit considered as a plain one-valve oscillator. When, however, variations take place in the control-valve anode circuit at speech frequency, very large surges are set up in that of the power valve, which may approximate to the original high-tension d.c. potential and so sweep the output from nearly double its steady value to almost zero. To give some quantitative idea of the forces involved, the following data, taken from

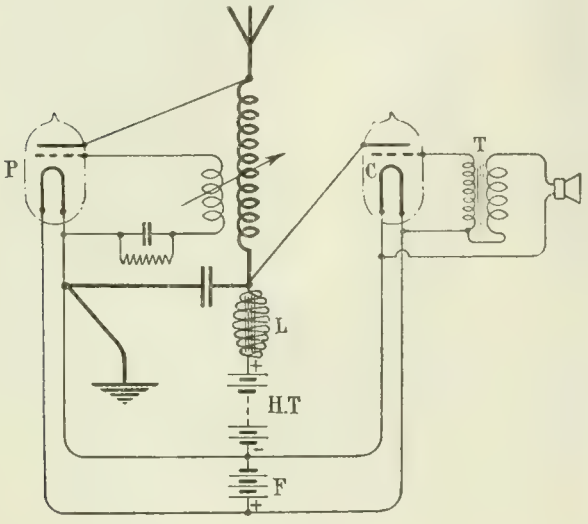

FIG. 3.

the small 20-watt R.A.F. set working on 600 volts high-tension d.c. supply, may be interesting.

Swing of grid potential on control valve, i.e. potential change on secondary of transformer with a loud vowel: 90 volts each side of zero, or 180 volts total.

Surge voltages across choke coil measured on electrostatic voltmeter on no load: (about) 700 volts; on load, that is with power valve in operation, 300 to 400 volts.

It is important to notice that although the control valve does not appear at first sight to contribute to the output, it actually does so; for the changes induced by it do actually swing equally above and below the line of normal output, that is, of the "carrier wave," albeit they are too rapid to produce any effect on the slowly acting aerial ammeter; and thus the choke control is of approximately double the effectiveness of one valve with grid control, whose variations can only be between normal and zero output. It is not ordinarily possible with two similar valves to produce changes quite equal to the output acted on, which is in many ways an advantage, as it makes for stability; and under certain circumstances it may be an improvement to add a third or magnifying valve in the control system.

Choke control proved pre-eminently suitable for air working, and no other method of modulation survived in competition with it. There are absolutely no critical adjustments anywhere. Almost every constant can be changed within quite wide limits, and though it may thus be caused to work more or less efficiently, it never reaches a point of complete failure. Moreover, where the set is subject to considerable increases of anode potential, grid control, which is a constant depending on the microphone system, becomes less in proportion to the output; whereas in choke control, since the modulating valve is fed from the same high tension, the "degree of control" is subject to this diminution.

The action of the choke was subsequently investigated with more accuracy than was possible in the hurry of war design, and some interesting results were obtained. For a sound frequency of 750 per second an inductance of not less than 5 henries is required; after that, the curve flattens out, and almost any higher value is immaterial. Resistance, as such, however, is always detrimental. The author has suggested, but never tried, the deliberate filtering out of the lower speech frequencies by too small a choke coil, in order to favour the higher harmonics.

In practice these are so important that the action of the iron core, while by no means negligible, is not preponderant; and, in fact, the best results often seem to be given by a choke coil in which the core is already saturated by the permanent feed current.

The little 20-watt choke control set, designed by the author on the principles outlined above, was very successful and became the standard R.A.F. set with which all the air transmission has, up to the present, been done.

Turning now to what may be called the accessories and general lay-out of the set (Fig. 4), one of its features, which was largely responsible for its success, was the use of "remote control" (which will be treated of at greater length in speaking of the receiver).

Things were so arranged that the set proper could be mounted at a distance in any convenient position, and only a very small control unit for operating it was brought within reach of the user's hand. In the case of the transmitter no adjustments were necessary, as a fixed wave-length, a definite aerial, and fixed reaction were used, so that the control unit carried only a switch, an aerial ammeter, and plugs for microphone and telephone receiver. The aerial ammeter was for the user's purpose merely an indicator that all was well, and he needed to pay no attention to its exact reading.

The switch fulfilled rather a complex function, as it made or broke the dynamo field, filament and microphone circuits, so that when it was off every circuit was dead. Remote control not only was useful in machines where space was strictly limited, but tended to mental directness—a very important point in war instruments—by removing from the user's contemplation all technical complexities.

From his point of view, then, it was necessary merely to

switch on and talk. Simplification could go no further; but how necessary this was, can only be appreciated, perhaps, by those familiar with air work. It is probable that much of the British lead was due to consistently designing to fulfil at all costs the needs of actual service conditions, rather than to a laboratory standard.

Although the first telephone had been supplied with high-tension current from dry cells, these had been completely superseded by small air-driven generators,

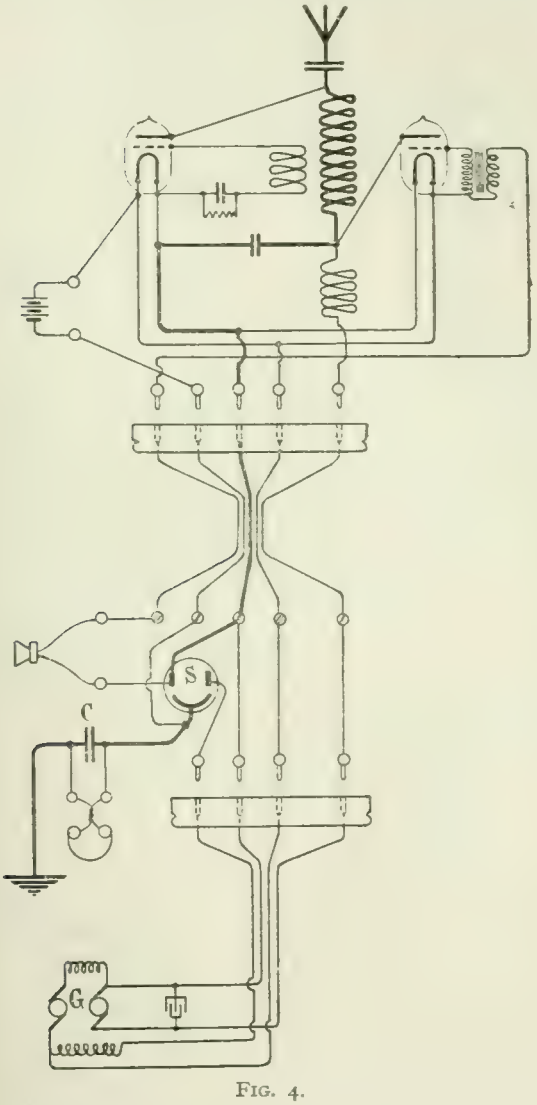

FIG. 4.

the improved descendants of one made for the author by Mr. Mackie early in 1916. Briefly, the standard generator (G) adopted gave about 600 volts from one commutator at its normal speed of 4,000 r.p.m., while the 6-volt filament accumulators were floating across the low-tension side. Moderately good electrical regulation was provided by a demagnetizing field-winding system, and in this way the size of the accumulator had not to be very great.

A small but interesting point about the set was the provision of "side-tone." It was found to be highly important that the speaker should be able to hear the effect of his own voice, and to do this in the simplest possible way a condenser (C) of about 5 jars' capacity was placed in the earth lead, and across it a pair of head receivers was connected, which were thus enabled to pick up the low-frequency effect. By connecting another pair in parallel, the other occupant of the aeroplane could also hear what orders were given.

Such then, very briefly, was the complete set as originally used in two-seater machines, for transmitting only, except that we have not yet treated of the microphone proper.

The importance of this is obvious, and only the barest outline can be given of what is a complete subject in itself; one in which opinion constantly sways from side to side, and which is at once difficult and easy. Opinion is no loose word; for in telephonic work under air conditions it is almost hopeless to expect exact or definite results from one experiment, and the only real guide is the mental summary of prolonged experience.

The disturbing elements may be set down as: (1) mechanical, and (2) acoustical. In the former the principal are the shaking up of the carbon granules by movements of their container, and the slow distortions of the diaphragm under varying air-pressures. Neither of these difficulties is very serious, and the first-named is almost completely eliminated by holding the microphone in the hand—the finest possible shock absorber.

The acoustical difficulties are far worse, and principally lie in this: that the noises which it is desirable to reject are of the same order as the sounds that are to be accepted.

After much experiment the Gordian knot was cut thus: by devising a microphone almost insensitive to sounds of the noise intensity, but responsive to the powerful concentrated sound waves of a voice impinging upon it from a very short distance. In other words, the voice was raised to a higher power, as it were, by speaking very loudly, and thus two distinct orders of intensity were produced, which could be separated. By choosing a suitable thickness of diaphragm, size of granule, tightness of packing, etc., combined with heavy damping, a satisfactory microphone was arrived at. It appeared curiously dead and ineffective on the ground, but seemed to take on a new sprightliness in the air. Of course in the quieter types of machines a more sensitive and more normal microphone was not only possible, but better; but nothing else was able to work so effectively in, say, a noisy Bristol fighter. A microphone has recently been patented with adjustable damping,* which ought to prove very useful.

We now turn from transmitting to its complement, receiving in the air. When the general uproar is remembered, the difficulties need no emphasis. The problem here was to combine considerable sensitiveness, loud signals free from distortion, and the minimum of adjustment.

It was only comparatively lately that high-frequency magnification became sufficiently manageable for introduction into aircraft, and low frequency could not be

* By Captain J. M. Furnival: Patent No. 16712/1919.

pushed very far without making a set far too sensitive to mechanical shocks. The arrangement which, as the fittest, survived, consisted essentially of a detector valve with reaction, and two note magnifications. The detector valve was not energized direct from the aerial, but through a so-called "aperiodic" circuit, which was really a circuit approximately syntonized by its self-capacity. This has always been found to reduce magneto noise considerably.

The application of remote control to the receiver really antedates its adoption on the transmitter, and is not, as with the latter, a mere matter of mechanical lay-out, but involves a technical point of some interest.

In some air-trials with the early 1916 soft-valve receiver, it was noticed that to alter the filament brightness made a very convenient way of finally controlling the reaction, after the circuit had been set near the critical point; and at Captain Furnival's suggestion a "banjo wire" resistance was made up and mounted on the joy-stick, so that the pilot could make the last fine adjustment himself. Subsequently, during the continuance of the general efforts to produce a really satisfactory aircraft receiver, when many a promising design wilted in the fiery trial of actual air work, the author persevered with the principle and had the satisfaction of seeing the "remote control" prove its usefulness.

The principle involved is, that the increase in emission caused by brightening the filament of the detector valve, whose anode current is concerned in the reaction, steepens the characteristic curve and so determines the oscillatory condition, when the circuits have been adjusted near the critical point; a condition which can easily be provided for in the design. The adoption of this principle had a large share in the success of the aircraft telephone, partly for the mechanical reason of having only a small control unit near the user, and also because to alter the reaction electrically in this way makes but an infinitesimal change in wave-length; whereas in mechanical methods small changes of capacity are inevitable with every adjustment, and necessitate a slight retuning, so that it needs some skill and finesse to get the best results. With this remote control, however, the user could get the tuning once for all, and adjust the reaction freely for the best effect by a safe and easy change in a low-frequency non-oscillatory circuit.

The remainder of the receiving circuits calls for little comment in a brief survey such as this, as they will be clearly understood from Fig. 5, and attention should now be given to the next step in advance.

Although prior to the War high-frequency magnification by resonance methods had been in use, there was a general recrudescence of attempts to effect it by simple means, aperiodically if possible, in which the French experts had taken a leading part. This resulted in such methods as the well-known condenser-resistance circuit, and one in which transformers with an iron core, highly laminated, were employed to deal with radio frequencies, and worked efficiently over large ranges of wave-lengths. The whole subject at this stage was somewhat nebulous until Captain Round, in a few weeks' admirable investigation, unified and correlated the various circuits, showing how all such transformers could be considered to be essentially resonance transformers, differing only in damping; so that it lay with the designer to choose small damping, large magnification per valve, a limited number of valves, small range of wave-length and a rather tricky circuit, or the reverse of all these, resulting in a stable flatly-tuned arrangement—or any intermediate conditions. Special low-capacity valves were introduced, so that the damping produced by them could be made a maximum, and high-frequency magnification was tamed and harnessed. A cascade series of such valves could be set up, working with fairly constant efficiency over a large range of wave-length, so that no tuning (within these limits) was needful except that of the circuit applied to them.

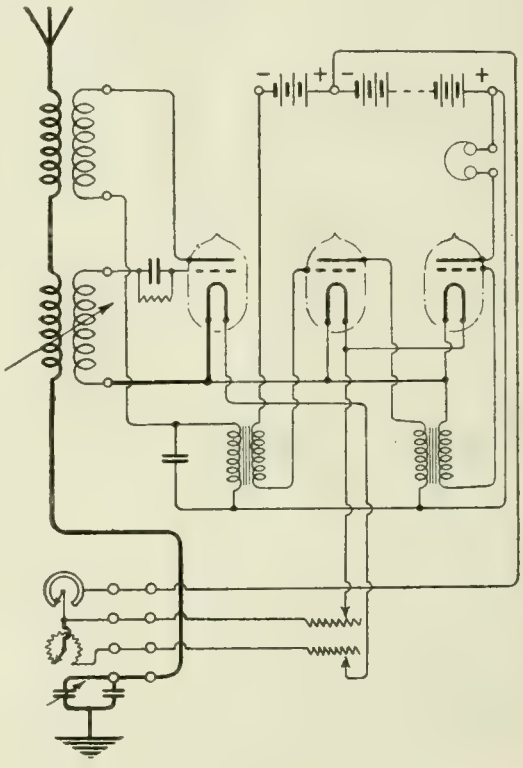

FIG. 5.

The first fruit of this advance, as far as aircraft sets were concerned, was a five-valve receiver, designed by Major Whiddington, in which a choice was made of two high-frequency magnifications and two low, with a detector valve.

This set, which unfortunately could not be manufactured in quantities in time to play much part in the War, was, as compared with the former three-valve receiver, about 10 times as sensitive for strong signals, and 30 times for weak ones.

It was intended for use with fixed aerials rigidly connected to the wings and fuselage of the aeroplane—as opposed to the trailing aerial, which was a great embarrassment in fighting. In spite of the diminished radiation of such an aerial, the increased sensibility of

this receiver approximately restored the usual range. Fig. 6 represents a typical circuit of this kind and shows one high and one low-frequency magnification, with a fine-grid rectifying valve between. Increased sensitivity as well as the nearer average approach of the aerial system to the source of disturbance, made more apparent, however, one of the great bugbears of air work where great sensitiveness is necessary—magneto noise.

This, again, is a subject in itself, on which a vast amount of work has been done; and as it applies equally to all aircraft wireless, no attempt will be made to treat of it in the present paper.

Since the new type of receiver had not come into general use up to the time of the Armistice, all the actual work was done with the three-valve receiver and transmitter already described. Trailing aerial wires of 120 ft. length were used in the transmitting machines, with an aerial current of the order of 0·4 ampere, while the receiving machines had aerials of from 80 to 100 feet in length. The normal safe working range from machine to machine was about 4 miles (though this was often very much exceeded), while the range to a ground station was from 20 to 50 miles or more.

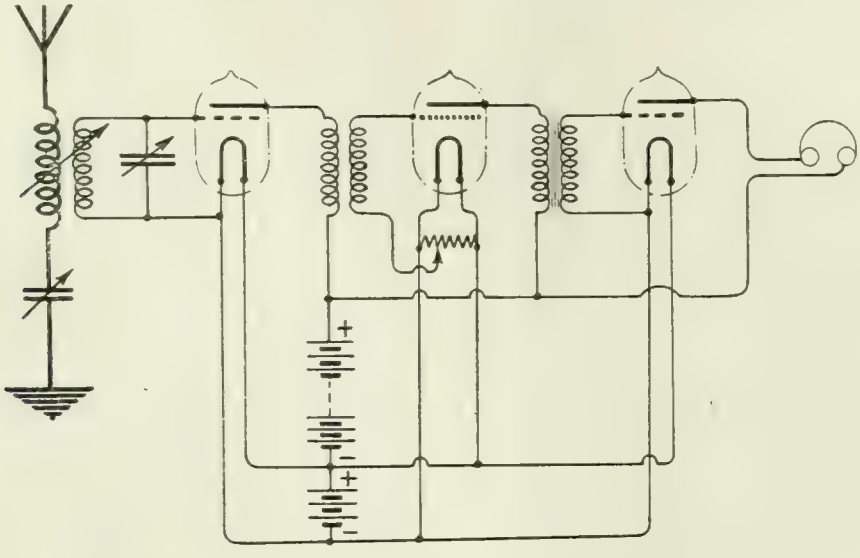

Fig. 6.

A flight or squadron of machines equipped with this apparatus could set out and fight or manœuvre in formation under the orders of their commander, whose machine only was fitted for transmission. So great was the importance of telephony considered to be, that a special school of wireless telephony was instituted under Captain Furnival, who had been one of the author's earliest assistants, and through this school passed every week about 36 fighting pilots for a course of instruction in using the apparatus and in the important art of proper articulation in the air. Special wireless officers also were trained at this school for the task of equipment and maintenance, and thus a whole organization grew up, as wireless telephony threatened to supersede all other means of communication for aircraft.

It took on great importance, too, for home defence against air raids; and a chain of ground stations of considerable power was put up (technically exactly similar to the aircraft transmitter on a larger scale) which were capable of transmitting up to about 100 miles to a machine in the air, in order to warn the patrols of the approach of an enemy. Telephony from the first of these stations was loud enough to interfere with work overseas in the neighbourhood of Arras. This work involved the fitting of receiving as well as transmitting gear in the leader's machine, and from this and other causes arose a demand for both-way working, which was easily satisfied by fitting both the standard sets in all necessary machines and arranging some form of switch-over.

In consequence of the greater ease of reception at a quiet ground station, and its superior transmitting power, the to-and-fro ranges became approximately equalized, in spite of the disparity of output, and a machine could speak or be spoken to at distances of the order of 70 to 100 miles.

After the signing of the Armistice the Cologne postal service was equipped, both ground and air, entirely with the little aircraft sets and some remarkable results were obtained. The ground stations, which had 70 ft. masts, were set at 50 miles apart, and could transmit 30 miles to a machine, or receive from a machine at a distance of about 50 miles. These are conservative figures, and frequently an intermediate station could be omitted and a machine could be in communication with three of the stations on the route. This was installed and equipped by a wireless telephone section organized for the purpose at Marquise. The central station on this route handled 5,000 messages during the 5 months it was in operation.

It only remains to indicate the lines on which the most recent apparatus with which the author is concerned is developing.

The International Convention having laid this down as the maximum allowable, the transmitter will deal with an input of 100 watts, and choke control will be retained. All types of transmission will be provided for. The receiver will have three high-frequency magnifications and one low, making with the detector five valves, and the combined transmitter and receiver will be worked from one remote control. Batteries will have to be retained at present for filament lighting, but they can be small ones floating across the generator; and there seems good reason to hope that in the near future a perfectly silenced and regulated generator will permit of the abolition of the battery, all current, even for the receiver, being supplied direct from the dynamo.

Ground stations will be equipped for direction-finding with a transmitting mast one or two hundred yards away controlled from the receiving building, and matters will probably be so arranged that the ordinary P.O. land lines can be plugged direct on to the wireless, so that a man may talk direct from his office to a machine in the air.

Unfortunately, switching-over will still be necessary until such time as the ideas which will shortly be set forth in a paper by Captain Eckersley come to fruition.

In conclusion the author wishes to express his thanks to the Air Ministry for permission to use the information given in this paper, and he would like to pay tribute to the memory of the late Captain Cecil Marks, to whose enthusiasm and encouragement was due almost the very birth of aircraft telephony, and whose death in action was a real loss. Moreover, no paper on this subject would be complete without mentioning the names of Captain McDougald and Captain Furnival, the author's earliest assistants and co-workers, or that of Major Robert Orme, who was for so long the loved and able Commanding Officer of the R.F.C. experimental wireless.

Discussion.

Captain J. M. Furnival: An interesting point in connection with the development of the pilot-operated set is that of the substitution of high-frequency magnification for the reaction and low-frequency circuit employed in the Mark III tuner. This is surely a big step in advance not merely from the point of view of a gain in sensitiveness, but rather of increase in reliability. To depend on reaction for ranges, the greatest care and experience is necessary, especially where test flights are few and far between. It is rather a problem to arrange an efficient ground test which will indicate truly that the set will come up to oscillation point in the way it should in the air. I think this was one of the main troubles of the maintenance officers, and one which will quite disappear with the introduction of high-frequency magnification. Under the subject of speech control, the author mentions that in certain conditions it is an advantage to employ an additional control valve on wireless-telephone transmitting sets. Such a system was successfully applied, I think, by Captain Murphy to an R.A.F. 11 transmitter at Marquise. In this case a small 20-watt service valve was successfully employed, thereby considerably increasing the efficiency of the station. There is a point in connection with the design of the air microphone which is perhaps worth mentioning. Not only is it necessary to choose a diaphragm of suitable thickness, but the actual material of which it is made is important. Various substances were tried, namely, carbon, steel, ebonite, celluloid, aluminium, and mica. Mica is the best, probably being a substance the natural period of which is least affected by engine noise. Aluminium also gives good results. It is interesting to note that the diaphragm of a gramophone is made of mica, and in this case also there is a certain amount of extraneous noise, due to the needle rubbing over the record, which it is necessary to suppress as far as possible. I should also like to mention the work of the wireless telephone officers, both wireless and flying, of the Royal Air Force who by their enthusiasm and combined efforts broke down the barriers of natural prejudice and laid the foundation of an organized wireless telephone service, which it is obvious will play a large part in aircraft communications of the future. The time has come when telephone fittings and wiring can be conveniently incorporated in the actual design and manufacture of aeroplanes. In war time the work had to be done after the machine was in service. This necessity led to the formation in France of what might be termed a "Telephone Service Section" whose duty it was to equip squadrons and supply them with serviceable apparatus and trained personnel. After the Armistice this Section equipped the Folkestone-Cologne mail route, both ground stations and machines. Machines were flown over to the depot, and within two or three days were fitted, tested, pilots trained, and helmets fitted for head receivers. One test flight was made in which the pilot operated his own set, and if passed as proficient, he returned to his squadron. A careful check of the working of the communications was made by arranging for an inspecting officer to fly periodically up and down the route and keep a careful check on the working of the stations.

Captain H. J. Round: The author and I have worked together a good deal during the last 10 years on various wireless subjects, and we have usually been in agreement; but during the early stages of the war I have very distinct memories of many attempts on my part to divert his work because of certain difficulties and many objections I saw to wireless telephony in the air. In the main he was correct, but in one or two particular cases I still think I am right. One case I can call to mind was the question of flight control. This was, I believe, worked out very completely but never actually put into war practice. All the author's wireless telephony was done with small power, in fact large power was not possible at the time. Owing to this use of small power, the immediate answer of the enemy to

our flight control would have been to fit their fighting flights with ½ kw. quenched-spark jamming outfits. Our own flights, trained to manœuvre with wireless telephony, and not so well trained to visual control, would have been at once at a disadvantage and I could see no immediate technical answer to their jamming. The large organization worked out for flight control would have thus been rendered useless until a much more powerful set was evolved. Anyhow I think this particular case points every time to the use of more power whenever wireless is used in active areas, and where interception can do little harm. Peace sets are being more generously designed, and, from the standpoint that our peace sets should be as adaptable for war as possible, this is a very good point. I should like to challenge the author on his statement at the bottom of page 380, col. 1. Although both the grid and choke controls are actually very complex in action and it is difficult to say how much of any one action is coming in, grid control in the main is a method of choke control where the same valve is used both for voice magnification and for oscillation purposes. The grid control is very considerably improved by inserting an anode choke, and when this is used the power considerations are the same, and generally the aerial ammeter does not move when one is speaking. I think that, except for small sets, the days of both anode and grid control are over. In some recent work, I have gone back to the circuit of Fig. 1, one of the best methods for controlling large power with the minimum voice distortion, of course with the microphone replaced by instruments which will handle more current.

(*Communicated*): I should like to add a short historical sketch of some of the valve transmission work we did from 1913 onwards. Although the work was for the most part on telegraphy and not telephony, the apparatus involved was practically the same. In 1913–1914 we were developing a valve system of sending and receiving both telephony and continuous waves. Such a system was evolved and practical apparatus exhibited early in 1914, various patents being taken out. This work was of course developed on the lines indicated by the work of De Forest, Lieben, Reiss, Meissner, and Franklin. During this period we evolved, amongst many other things, the anode and grid control methods, and also the plain aerial method of using valve transmitters. Unfortunately, lack of vision—perhaps the thought that they were rather obvious things—prevented the grid and anode controls being patented, but I well remember that the grid control was produced as a natural evolution of the anode control because it used only one valve, and that was a very good point in the days when each valve required watching. Both methods were actually tested at Marconi House and elsewhere, and good results were obtained. The high-frequency control was also evolved, similar to the method mentioned by Mr. Turner, and this was patented. At that time, currents in the aerial so seldom exceeded 1 ampere that microphonic control was always found to give the best quality of speech and was more usually used. When the war started, other more important work stopped development for a time, and Major Prince carried on the development of our set to make it suitable for the air. During 1915 the development of the self heterodyne and the use of plain aerial circuits in reception suggested to me the revival of the plain aerial circuit which I used in 1914 for continuous-wave transmission. Urged on by the late Lieutenant Hyde Thomson, to whose brilliant imagination I should like to pay great tribute, we made up the first continuous-wave plain aerial transmitters for aeroplanes, airships, and ground stations, and, I believe, made the discovery of the extraordinary range possible with short continuous waves using self-heterodyne receivers. I will quote three cases of this. Late in 1915, Lieutenant Tomlinson, with a 20-watt continuous-wave plain aerial transmitter constructed in my laboratory, went up at Wormwood Scrubbs in a small S.S. airship, and his signals were easily received with one valve 400 miles away at Aberdeen, the wave-length being 1,200 metres. Major Binyon, flying from Eastchurch to Eastbourne in an aeroplane with the same set, was read in London with very loud signals, and the operator listening at Eastchurch reported hardly any change in strength during the complete flight of the plane. Thirdly, a similar set erected at Folkestone, with a 70 ft. aerial wire completely inside a two-story house, was read easily at Marconi House, about 60 miles away, on one valve, and was also simultaneously read at Calais. One of these sets was, I believe, actually the first continuous-wave set used in the British Army. These results can be repeated at any time as everyone knows now, but I believe they were new then. In all cases the practical details of the development were carried out by others.

Professor R. Whiddington: The apparent broadening of the wave during telephony is really fundamental and unavoidable. A slightly damped (telephone) receiving circuit, therefore, while responding to the radiation as a whole, will always select that particular frequency for which it is actually atuned. This phenomenon, while always present in some degree, is particularly marked when the radiation is weak, and in consequence the receiving circuit is worked very near the limit of reaction. In such a case as this, loud speech may be obtained, but distorted to such an extent perhaps as to be unintelligible. An interesting experiment, and one easy to carry out, affording a practical demonstration of these multiple waves, is to analyse by an ordinary wave-meter the radiation from a valve oscillating-circuit using an alternator as the source of power. The carrier wave is then modulated according to the frequency of the alternator and the wave-meter detects at least two frequencies on either side of that corresponding to the radiating circuit, the frequency difference depending on the period of the alternator. Mr. Turner has referred to the possibilities of the "dead aerial" system in wireless telephony, the system in which the carrier wave only comes into action when the voice affects the microphone. During the war I carried out experiments resulting, I believe, in the first successful two-way telephony along these lines.

Captain P. P. Eckersley: It should, I think, be realized by those who have read this paper that the achievement of bringing the aircraft telephone to its present state of perfection has been a problem of pro-

paganda as well as a technical one. Whereas early in 1915 the average pilot looked upon all wireless on machines as "another gadget," in 1919 certain pilots on the postal routes refused to fly without a wireless telephone. On the technical side the introduction of remote control, the simplicity of the adjustments, and the lightness of the apparatus have all helped to convince the non-technical users of the possibilities of the apparatus, and for war purposes it is difficult to see how the sets could have been bettered. On pages 377 and 378 the author records how spoken messages at St. Omer were heard 100 miles away, the transmitting aerial current being only 0·25 ampere. The wave-length used was 300 metres, and this largely explains how such a remarkable range was obtained. The standard R.A.F. set used 450 metres and an aerial current of 0·4 ampere, and in the Cologne postal route gave remarkable ranges. It seems therefore, from a study of these results, that short wave-lengths are very desirable for aeroplane telephony. The International Air Convention has, however, legislated that the aircraft wave shall be 900 metres, a rather retrograde step when it is realized that the resistance of an aeroplane aerial is high in any case. Even though we are allowed five times the power of the author's set, this is therefore not being utilized to anything like its best efficiency, since the radiation resistance is cut down many times and introduces further problems in winding high-inductance aerial coils which necessarily militate against efficiency. Jamming is of course a factor to be very seriously considered, but if free æther could be sought among the lower wave-lengths the designers of modern aircraft gear would be less hampered and could for the same ranges construct lighter apparatus. On pages 378 and 379 the author refers to methods of modulation and discusses them in relation to the receiver. I think the designers were very happy in their choice of the choke control, as it gives an ideal and stable method of control. What perhaps is not sufficiently emphasized in the paper is the fact that choke control uses the power available in the carrier wave to a maximum. That is to say, it controls the intensity of the antenna current not only below the line of constant output but above it. Any control which merely reduces output must on the face of it be less efficient than one that both increases and decreases it. Neglecting therefore the power absorbed in the control valve, the wave-length change and the bad regulation of the choke transformer, one would expect the current change apprehended by the detector to be twice as great with choke control as with, say, grid control. Mr. Turner has referred to choke control, and has said that the method is wasteful of power. I do not think that is truly so, because, when it absorbs power, that power is stored up in the choke and is released afterwards, being analogous to a vibrating pendulum. I think the circuit that Mr. Turner described is a very old one and very well known. Captain Round used it with considerable success, and in America I believe it is very largely used. Professor Whiddington referred to the quiescent aerial system. I think one of the troubles about this system at present is that it gives very poor speech. I do not think much has been gained, even if the quiescent aerial system is successful, the problems of receiver protection still remaining. Speech quality with the choke control was, I think, very good, but it becomes increasingly apparent that the characteristics of the receiver influence speech quality nearly as much as the circuits of the transmitter. This is brought out on page 379, where the author points out that by pushing reaction to its limits freak results are obtained. Reaction on the receiver, although tending to raise the intensity, certainly distorts speech at times. This may be due to the narrow resonance curves excluding essential frequencies in the received waves, or again may be produced in the detector valve by intensifying the carrier wave so that "wipe out" is produced. The consequent distortion may be rectified by mistuning, but this quality of the largely reactioned receiver is not a good one as it makes two adjustments mutually interdependent, a bad quality for pilot-operated sets. Thus the line of development is indicated in the author's concluding remarks, where he points out that the latest types of receiver employ high-frequency magnification which makes intense reaction less necessary for a given range and so gives two independent adjustments, signal intensity and tuning, both of which should not greatly interfere with quality. Those who have had much experience with telephony have perhaps been sometimes worried by "breaking" of speech, as the author points out on page 378 in connection with one experimental circuit. Such breaking can sometimes occur even with choke control, although it is less susceptible to this trouble. This is, I think, bound up with the oscillating circuits and particularly the position of the mean grid volts line on the oscillating valve. There are broadly two possible states of oscillation bound up with the mean grid volts, one the trigger condition where the oscillation dies suddenly when the reaction is reduced, and the other condition where a lingering death occurs. In the sudden death or trigger condition, it is possible if the reaction is on the weak side to get broken speech. In the other condition I have never noticed this tendency, and even the substitution of a coarsely adjusted buzzer for the microphone will not stop the system oscillating. Where it is not possible then to over-control and get breaking speech, it is advantageous sometimes to introduce a second magnifying valve. This has a particular application where weak land-line speech has to be relayed on to a wireless system, but pays even where a voice is speaking directly into the telephone. The author has skimmed over the thin ice of magneto noise, and those who have done much air work sometimes wish they could dismiss the subject as lightly. The problem is very acute, first from its very nature and, secondly, because it is next to impossible to experiment in the air. It is useless to do much on the ground, and once in the air arrayed in a heavy flying coat, a tangle of wires round one's feet, a few suspended swaying boxes dotted about round an already cramped cockpit, and a pilot who wants to go home, coherent thought becomes almost impossible. Results, so far, have been obtained by avoiding machines that were notoriously noisy, but much remains to be done. Shielding can in many cases be carried out *ad nauseam* without any diminution of the noise, whereas some small, apparently foolish,

change in the connections produces the longed-for peace.

Mr. L. B. Turner: The author has devoted some attention to the system of choke control embodied in the very elegant telephone transmitter of his design, and he seems to suggest there is some degree of mystery as to how it functions. Referring to Fig. 3, when the voice raises the grid potential of C, the anode tries, as it were, to suck in extra current; but as choke L keeps the high-tension battery current more or less constant, the top end of L falls in potential, and C is supplied only at the expense of P. There is thus no optimum value for the inductance of L; the larger it is the better, but when once its impedance is very large compared with the mean anode resistance of P, nothing is to be gained by making it larger. The author reports that at 750 periods per second an inductance of 5 henries was nearly as good as any higher value. The reactance of this inductance at this frequency is $2\pi \times 750 \times 5 = 24{,}000$ ohms. This, being already large compared with (say) 5,000 ohms as the anode resistance of the oscillating valve, is nearly as good as an indefinitely

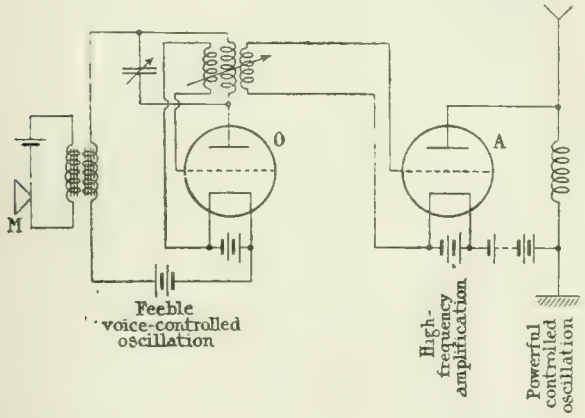

FIG. A.—Wireless telephone transmitter.

great inductance. As the author points out, the choke control has many virtues; but I think he gives a wrong impression when he says (see page 380, column 1) that "although the control valve does not appear at first sight to contribute to the output, it actually does so." The control valve varies its mean consumption with alternate gulps and vomits of electricity according to the microphone stimulus on its grid; but the mean power of the high-frequency oscillation is not affected by it. On the other hand, the control valve consumes a steady mean power, which is sheer waste from the point of view of efficiency as the ratio between output and input powers. In small aircraft transmitters, this is not of much significance; but with these circuits, as the antenna power is increased, so, *pari passu*, must the power wasted in the control valve be increased. With the primary object of avoiding this waste, Captain R. H. Wagner and myself devised the type of telephone transmitter shown in principle in Fig. A herewith. Here O is a feeble oscillator controlled in amplitude by the microphone M, and A is a single or multi-valve amplifier inserted between O and the antenna. Thus, however powerful the transmitter, the microphone has to modulate only a feeble oscillation, the modulated oscillation being subsequently amplified to any desired extent. An incidental advantage of this arrangement is that it reduces the difficulty of attaining both-way telephony referred to in the paper. For both-way telephony, the oscillator, or at any rate the antenna, must oscillate only while the voice is agitating the microphone; and the feebler the oscillator, the more easily is this accomplished without loss of articulation. In conclusion, I wish to refer to another point respecting modulation by the voice, not specifically mentioned in the paper, although I think it was the author who first brought it to my notice during one of those stimulating friendly discussions in which at one period during the war he and I and our colleagues used to indulge. When there is a large unmodulated residuum in the transmitted oscillation, the uncontrolled portion may yet be of some service at the receiver in maintaining good rectifier efficiency for very weak signals, as in the case of heterodyne reception. But this is a very uneconomical way of obtaining the augmented detector efficiency, since precisely the same result can be produced more completely by an independent heterodyne at the receiver, tuned dead-on so as to produce no beat-note. This kind of zero-beat heterodyne reception is of great value in telephony, and does not seem to have received the attention it deserves.

Major T. Vincent Smith: The sight of that old piece of apparatus calls back to my mind the early days at St. Omer when the author and Captain McDougald came over to show us what they had done in the way of wireless telephony. We tried it in all manner of ways, and so long as it was in capable hands it never showed any signs of failure. I also remember very forcibly Lord Kitchener's expression when he put the telephones on, rather unwillingly at first, and began repeating every word that Captain McDougald was saying. He said afterwards that it was one of the most interesting things he had seen on that visit of his to France. I also remember the panic that ensued at Headquarters when information was sent over from Lowestoft that every word had been heard there. It stopped our experiments for quite a long time, because the Intelligence Staff thought that the enemy would get valuable information from our messages. However, when that restriction was withdrawn by Headquarters there was obviously a lot of spade work to be done before we could apply wireless telephony to anything like practical use in the line, and I pay full tribute to the author, Major Orme, and everybody associated with them for the way in which they met essential suggestions regarding the simplification of the apparatus. The design of aircraft wireless apparatus for war use is profoundly modified by the personnel who have to use it, and I am glad to see that the author acknowledges those difficulties which I had to face, and which forced me to insist on simplification of design, and this I am bound to say he was always able to meet. The main point about the apparatus was: what was it to be used for? It was most inadvisable to show an article like a wireless telephone to the Higher Command, who imagined that one had only to have a telephone without

wires in order to solve all communication difficulties; whereas, of course, it was our duty to modify their enthusiasm considerably, otherwise they were inclined to ask us to do all sorts of impossible things. Although at first sight it might appear to be a useful substitute for the ordinary transmitting key, I am rather doubtful whether, except in certain cases, it is desirable to do away with Morse. I am convinced, it spite of what Captain Round said, that there is one extremely important application of the wireless telephone, and that is inter-machine telephony for the purpose of regulating a formation flight. I think it is the most important use to which the wireless telephone can be put. The question of jamming, I agree, is very important, but, after all, we had to deal with that along the whole of the Western Front. The Germans never succeeded in jamming us to any serious extent. I think it is a sign of inferiority to have to jam one's opponent, and we were always proud of the fact that we did not need to jam them.

Mr. H. M. Dowsett: I would ask the author whether the first working set—as distinct from the skeleton model made up at Brooklands on which speech was first received—was not made up at the Marconi works under the supervision of Captain McDougald. With regard to the choke control, it is interesting to record that early in 1914, in tests which were carried out by Captain Round between Chelmsford and the author's house at Danbury, a choke was used in the anode circuit of the oscillating valve which had the same function as the choke in the R.A.F. circuit, although it behaved less efficiently, as the modulation control was exercised through the grid circuit of the same valve instead of by means of a separate valve acting on the choke direct. I should like to know the author's reason for advocating the filtering out of the lower speech frequencies. Unless the valve, the method of control, or the microphone unduly favour such frequencies and the suggestion is put forward as a means of correcting this, it is not obvious why the distortion which must result, and which must impart a squeaky character to the speech, is likely to be an improvement. It is well known that the higher harmonics are of great importance, and a voice with a high pitch is much more effective than one with a low, but does it follow that high-pitch speech would be still more effective with the lower frequencies removed? The necessity of heavily damping the diaphragm of the microphone in order to render it less sensitive to noise is one of those measures which it may be hoped will in time be rendered unnecessary. The baffle mouthpiece so far has not proved a success, but should it do so the more sensitive ground microphone could be used in the air with advantage. The selection of suitable materials for the diaphragm, as pointed out by Captain Furnival, may help considerably towards the solution of this problem. There appears to be no technical reason why the perfectly silent direct-current generator looked forward to by the author, which can be used for the high-tension supply of both the transmitting and the receiving valves, should not materialize at the present time. Generator noises are due partly to commutation and partly to field distortion by the armature teeth. By means of interpoles and properly designed brushes and brush-gear the commutation can be rendered sparkless; and by suitably slotting the poles so that when one conductor of a coil is opposite a tooth, say in a north pole, the other conductor of the same coil is opposite a slot in a south pole, equal and opposite harmonic electromotive forces will be generated in the winding and will neutralize each other. The wave-form of the terminal electromotive force will then depend solely on the shape of the poles and the arrangement of the armature coils, both of which are controllable, so that it should be quite possible to obtain an unvarying direct-current voltage.

Flight-Lieutenant L. A. McDougald: This paper gives a very comprehensive account of the development of aircraft wireless telephony during the war. A very considerable part of our work consisted in reducing the size and weight of apparatus, and of increasing its efficiency and simplicity of operation. The first experimental transmitter, of an earlier design than that shown in Fig. 1, had six adjustments, many of them critical. The final 20-watt set, as pointed out in the paper, required no adjustment. The soft valves in use in the early days were provided with a regulating device in the form of a pip containing a crystal of asbestos or other mineral. This, when heated, reduced the vacuum in the valve. It was the custom to heat the pip before a flight took place, but it often happened that when in the air one found the valve had become too hard to oscillate. In order to overcome the danger of applying a naked light, a small electric heater was devised which could be placed over the regulating pip. It is worthy of note that during the demonstration flight for the late Lord Kitchener a snowstorm was in progress. In consequence we could only fly at a height of a few hundred feet, and the fact that our speech was picked up by Lowestoft is therefore all the more remarkable. The trailing aerial always lends itself to variations of wave-length when the aeroplane is manœuvring, due to change of aerial shape. This difficulty is overcome by the use of the so-called "fixed aerial"—that is to say, an aerial rigidly fixed inside the wings and fuselage of the machine, from which it is thoroughly insulated. Dr. Whiddington has pointed out elsewhere (*Nature*, vol. 104, p. 630) that this wave-length change is due in part to a variation of anode voltage consequent on the changing speed of the wind-driven direct-current generator during a manœuvre. With a modern, well-regulated, wind-driven generator, I think the greater part of the change in wave-length is due to the change in shape of the trailing aerial. This is borne out by the fact that the effect was very noticeable with the original telephone transmitter, the source of anode voltage being a 600-volt dry battery. Very promising results have been obtained on fixed aerials for reception. Using the 20-watt transmitter and the R.A.F. Type-X five-valve receiver-amplifier, an "all-round" range of 3 miles and a "best position" range of 7 miles have been obtained. These ranges are not the limit for the reception of intelligible speech, but were considered to be safe working ranges. By "best position" is meant the best relative position of the two aeroplanes. Magneto noise is generally

more troublesome with a fixed aerial than with the trailing aerial, but it can be successfully eliminated by using high-tension cable covered with a flexible metallic braiding for all the magneto circuits. The metallic braid is "earthed" to the frame of the aeroplane at frequent intervals.

Mr. F. P. Swann: The author and several speakers have referred to the fact that on the occasion of the wireless telephone demonstration at St. Omer in 1916, the speech was heard at Lowestoft. I am quite sure the author will not think that I am trying to detract from the merits of his set if I suggest that a certain amount of the credit should be given to Lowestoft. This station was installed with the most sensitive receiving gear then known, and was doubtless responsible for a generous portion of the range covered.

Major C. E. Prince (*in reply*): As I mentioned in reading the paper, I had not intended to get into such deep waters as wireless telephony in the abstract, and confined myself to the practical application of it with which I was identified, simply because the whole subject was too wide to cover. Many of the points raised will, I hope, be touched on and extended in the discussion on Captain Eckersley's paper on "Duplex Wireless Telephony," and will, perhaps, be more germane to that subject than to my paper.

Some of Mr. Turner's remarks have already been answered for me by Captain Eckersley. On one point he seems to have misunderstood me. If he will read the paper carefully he will see that I never implied that there was any critical value for the choke; only that a certain minimum value is necessary, after which it becomes the equivalent of one indefinitely great. So that we really seem in complete agreement. I believe that he has fallen into an error in his treatment of the contribution of the control valve to the output. Or rather, while right about the action of this valve—whose effect on the total output is virtually to make the mean value remain equal to the normal unmodulated output of the oscillator—he seems to have forgotten that when one valve only is in operation the mean output will be something considerably less than the above steady output. All this quite apart from considerations of the maximum instantaneous excursions, on which, after all, modulation depends. The amount of steady anode current consumed in this valve when not in operation is a local question depending on grid mesh, and so on, and can be quite negligible. Taken in conjunction with what Captain Eckersley has pointed out, I think that this justifies the assertion that the control valve does make its due contribution to the telephonic or modulated output.

With reference to Professor Whiddington's remarks, I owe him a debt of gratitude for first clearing my ideas on this subject, some years ago. A radio frequency modulated or supplied at another, say, sound frequency, will give a group or family of waves of which the resonance curve will appear as a central ("carrier") wave accompanied on each side by a series of diminishing intensity, like the Crusader on the old memorial brasses surrounded by his family. It is quite plain that this is a mathematical necessity, and that consequently during speech the radiation is in the form of a constantly changing broad band or "spectrum" of waves, though it should be remembered that the subsidiary waves, being weaker, tend to disappear, and at great distances the "spectrum" narrows again till practically only the principal wave remains. But in alluding to the change of wave-length so far inseparable from all known means of modulation, I did not intend to refer to this phenomena, far less to controvert it, but rather to the slight change of frequency of the oscillator, that is of the carrier wave or central point of this spectrum. In telephony, as I visualize it, not only is this spectrum in itself compounded of the various spectra, each derived from a definite audio-frequency, fundamental or harmonic, but it is constantly changing with each speech sound; and, with its centre or "Crusader" wave, is also subject to a general fluctuation round about its normal unmodulated frequency, so that it is really a very complex matter indeed. In any case the principal difficulty of all wireless telephony is the means of modulation, and any contributions ought to be welcomed, because we cannot know too much about it. As regards Dr. Whiddington's reference to the dead or "quiescent aerial" system, his independent re-discovery of this corollary of choke-control filled us with great hopes, and it was no small disappointment to find that it had already been patented in America, and also to discover certain inherent defects which militated against speech-quality. This will no doubt come under consideration in Captain Eckersley's paper on "Duplex Wireless Telephony." At the same time I cannot help but consider it as the foundation of the probable future duplex system.

Major Vincent Smith has spoken about the simplification of the sets. It was due to him, very largely, that we were forced, much against our will, to simplify to the extreme. It is very largely because he made us "dance in chains" that we succeeded in arriving at this great simplicity, which meant all the difference between success and failure. He has referred to what may be called the mental or spiritual difficulties of the introduction of telephony in aircraft. We knew them too well, and only an unwavering faith in its possibilities in the most definitely difficult and unpromising field enabled us to see the victory of the spoken word. On behalf of those who worked with me, I should like to thank him for the kind things he has said about us.

I do not think that Captain Eckersley's or Captain Furnival's interesting remarks call for any comment by me.

Answering Captain Round, I am extremely glad that he has raised the historical side, because I am conscious that the text of my paper does not make clear, as it should, that while the novelty lay in their unprecedented application, the transmitting circuits employed in the apparatus I described were all reproductions of, or founded upon, those developed before the war by himself and his assistants. Before the war they had brought the small-power valve wireless telephone to a remarkably high state of development, and in June, 1914, demonstrations employing various circuits had been given between my house and the Marconi works, to representatives of the Army, Navy, and Post Office, so that in attacking the subject of aeroplane telephone

working the circuits and system were already at hand, and the problem was that of applying them to the novel conditions. Thus the first aeroplane transmitting set (Fig. 1) employed bodily his coupled circuit arrangement and was a direct adaptation of the ground set demonstrated by the Marconi Company in 1914. The great advance made by Captain Round by the "plain aerial" system of excitation for continuous waves was what gave the impetus to the search for a satisfactory method of applying voice modulations to such a circuit, and when, in the course of my experimenting, the problem was submitted to him, he came to the conclusion that a modification of one of his 1914 anode control circuits would be the most suitable; and, after some confirmatory experiments at Marconi House, gave me on 5th May, 1917, a sketch of the choke control circuit described, which was embodied in the Mark II transmitting set. It was afterwards found that the same idea was set forth in an American patent specification of the General Electric Company of America, and when the American Signal Corps brought over some specimen apparatus in 1918 it was found to be employing a system of modulation similar to that of our service instrument. I may say that, apart from the origination of the circuits, Captain Round's continual advice and help were of the greatest possible assistance also throughout the course of development. Turning to his remarks about grid and anode control, this opens up many interesting considerations of the exact relationship of his 1914 circuit (having the microphone transformer in the grid circuit, and a choke in the anode supply) with the later two-valve development. I agree that it seems correct to consider the former as essentially a choke control system, though with one valve only, and it was, I believe, recognized by him as such at the time. Where, however, no such choke is inserted, i.e. there is plain grid control, I would be inclined to think that there was an essential difference between the two arrangements: (1) where the anode is kept at a fixed potential by an unlimited source of current supplied through a negligible impedance, while the electrification of the grid was varied; and (2) where the latter was constant (except in so far as it was affected through the reaction coupling) and the potential of the anode varied. The actions must, however, as Captain Round suggests, be very complex. The title "choke control" has now, however, passed into common parlance as descriptive of the particular two-valve arrangement shown in Fig. 3.

Mr. Dowsett will, I trust, find many of his remarks answered by what I have just said. The first or Mark I set was made from my designs as he describes. The filtering out of lower speech frequencies was only suggested by me as a possible correction to be applied in cases where the latter might be unduly favoured. Human thought (in English) is principally conveyed through the consonants and higher harmonics, and squeaky speech, though unlovely, is intelligible; whereas speech in which only the lower frequencies exist conveys no meaning. When intelligibility is of the greatest importance, it might be worth while to exaggerate the frequencies on which it depends. It was merely a suggestion. The making of a microphone to work satisfactorily in extreme noise is, of course, one of the greatest difficulties of aeroplane work, and so far as our interminable experiments showed, all devices to reduce the external noise are merely changes rung on the theme of general insensitiveness. The best hope for improvement lies in quieter machines; and already civil aircraft are proving better in this respect than the fighting aeroplanes we had to equip. Mr. Dowsett is right in pointing out that it is by no means impossible at present to produce a generator quiet as regards ripple, or "telephonically silent." But this is only half the problem. There are generally high-frequency disturbances (akin to magneto noise) set up, mainly by sparking at the brushes, which are a still more serious difficulty where high-frequency magnification is employed. However, there seems good hope of finally conquering both difficulties, even with large magnification.

Mr. Swann has referred to the occasion on which speech with 0·2 ampere aerial current was picked up at Lowestoft from St. Omer. This was undoubtedly a magnificent achievement in reception, by a station equipped by Captain Round with the most efficient possible apparatus. My reference to it, however, was not meant to involve any estimate of the merits of either transmitter or receiver, but merely to point the moral of the efficiency of radiation of the shorter wave then in use.

THE PROTECTION OF ALTERNATING-CURRENT SYSTEMS WITHOUT THE USE OF SPECIAL CONDUCTORS.*

By Major KENELM EDGCUMBE, R.E.(T.), Member.

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INTRODUCTORY.

The disconnection of faulty plant or feeders, whilst at the same time maintaining continuity of supply, is at the moment one of the most pressing of the problems which confront the power station engineer and is becoming one of ever increasing difficulty as networks are extended, larger power units are installed and adjoining systems are linked up. Under present conditions, moreover, almost every network consists of a collection of cables laid at various dates, so that no system of protection which involves duplicate cores, pilot leads, conducting sheaths, or the like, can be regarded as a general solution of the problem. The methods adopted must be such as can readily be applied to the various sections of an existing system as well as to future extensions.

The author believes the four cardinal points of a protective system to be :—

(1) The maintenance of continuity of supply.
(2) Simplicity of the apparatus involved.
(3) Adaptability to existing gear with minimum alteration, and flexibility as regards future extensions.
(4) Economy in its true sense, having regard to the capital sunk in cables, etc.

The present paper is an attempt to show how these ideals can be attained by simple means with well-tried apparatus and without recourse to special conductors which, however desirable in themselves, are, more often than not, quite out of the question.

The fundamental requirements of a protective system have been admirably summed up by Mr. S. L. Pearce † as follows :—

" First of all we want to make sure that any consumer's fault, however severe, shall be cleared without upsetting the system. The same remark applies to the apparatus in any of the regular public-supply substations. If these two conditions be attained we come to the third point, viz. that a feeder at the main generating station should not be automatically disconnected except in the event of a fault to earth on any of its three phases. Then, fourthly, the main generators ought not to be disconnected from the busbars through any fault on feeders or consuming devices. They should only be cut off in the event of a fault on any of their own windings, with which can be combined overload protection to guard against busbar faults—a somewhat remote contingency."

The components of every system may be classified as follows :—

Independent feeders, single or parallel.
Interconnectors, single or parallel.
Ring mains, single or parallel.
Consumers' connections.
Generators, transformers, busbars, etc.

ADVANTAGES OF AN EARTHED NEUTRAL.

Intimately connected with the problem of the isolation of faults is the question of earthing the neutral point. Whatever advantages may, at one time, have been claimed for the insulated neutral, it is now fully recognized that the advantages are all in favour of earthing, and the protection against over-pressures (whether due to atmospheric effects or to intermittent earths), which is afforded by the damping effect of a resistance in the earth circuit, is seen to be so important that both American and Continental practice are fast following the lead given by this country. In the present paper, earthed systems alone are dealt with, since, in the author's opinion, the first step towards the attainment of satisfactory protection is to earth the system through a resistance. At the same time, many of the arrangements recommended are also applicable to insulated systems.

Apart altogether from the value of earthing through a resistance as a protection against over-pressures—into a discussion of which it is not proposed to enter—it affords a means whereby the majority of faults can be cleared in their initial stages as single-phase leakages to earth, instead of being left on the system until they have developed into short-circuits between phases. When it is considered that on a large system the magnitude of a short-circuit is almost unlimited and may well amount to half a million kilovolt-amperes, the vital importance of this is self-evident. The ill effects of a fault are impossible to predetermine and are felt to the remotest parts of the system in the form of over-pressures, breaking down of insulators, machinery falling out of step, short-circuiting of transformer and machine end-windings, and so forth.

The principles underlying leakage protection are by no means new, having been introduced in connection with the " leakage indicators " developed some 15 years ago under the then newly introduced Coal Mines Regulations. An early arrangement is shown in Fig. 1.* In this device the magnetic balance of the three currents

* The expression " protection," used in this sense, is well established, but in the author's opinion is somewhat of a misnomer. To speak of the " isolation of faults " would be better, since no circuit breaker " protects " a system against the occurrence of a fault. Its functions are limited to the isolation of the faulty section.

† *Journal I.E.E.*, 1914, vol. 53, p. 177.

* *Electrical Review*, June 16th, 1905.

is used, any inequality (due to leakage) being shown by a magnetic flux in the transformer core which induces an electromotive force in the secondary.

Fig. 2 illustrates the application of this principle to a circuit breaker.* The three-phase generator (G),

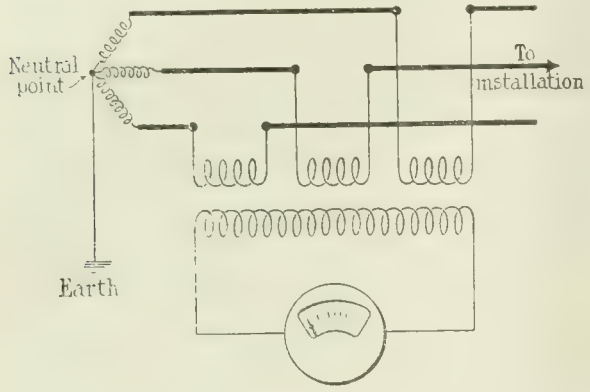

FIG. 1.—Early form of core-balance leakage indicator.

with earthed neutral, is connected to a feeder, the three cores of which are surrounded by the iron circuit of a current transformer (C T) having a single secondary winding, connected to a relay (R). Under normal

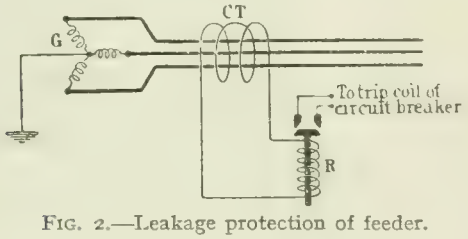

FIG. 2.—Leakage protection of feeder.

conditions, no matter how much the load may be out of balance, the sum of the three currents is zero and the resultant flux in the transformer core will be negligibly small. An earth fault on any phase, however, will

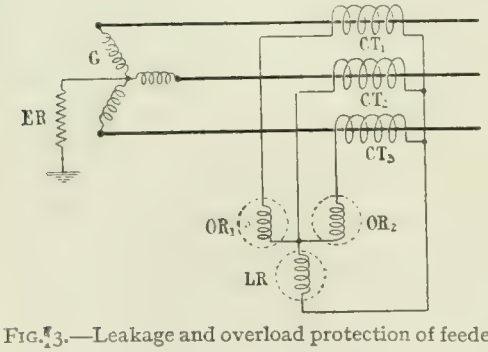

FIG. 3.—Leakage and overload protection of feeder.

upset the balance in the three lines and induce a current in the secondary of the transformer, causing the relay to operate and the breaker to open the circuit. Fig. 3 shows a similar arrangement, but in this case three separate current transformers are connected in star and the leakage relay (L R) is included in the common return.

An obvious objection to leakage protection when used by itself is that, should the fault either start as, or immediately develop into, a short-circuit between phases, there will be no out-of-balance current and, consequently, the leakage relay will not act. To obviate this, overload relays (O R_1) and (O R_2) can be included in two of the branches, as shown in Fig. 3, and under these circumstances one at least of the relays will act under all possible fault conditions, whether of short-circuits or earths.

Since one of the principal advantages of such an arrangement lies in the smaller current with which the circuit breakers are called upon to deal, it is obviously essential to limit the earth current, and this can best be done by an earthing resistance connected between the generator neutral and "earth" (E R in Fig. 3). The construction of such resistances and their most suitable capacities are dealt with later.

The Protection of Independent Feeders.

Fig. 3 shows a single outgoing feeder, and if this merely runs to a distributing point no further protection is required, beyond that shown in the figure. The relays O R_1 and O R_2 would be given a short time-lag (preferably an inverse function of the current) to prevent opening with a momentary, and possibly innocuous, short-circuit or overload. The leakage relay (L R) may be made instantaneous in its action, if thought desirable, but since the earth current is definitely limited by a resistance there is no objection to leaving such a fault on the system for a time and this is often advisable, for the same reasons as apply to overload relays.

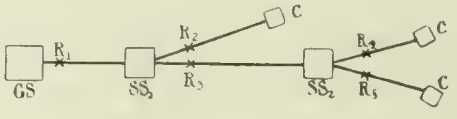

FIG. 4.—Single feeders in series.

In many cases the feeder will run to a substation from which other feeders radiate. Fig. 4 shows such a system in rudimentary form. G S is the generating station, S S_1 and S S_2 are substations, while C, C, C are consumers' installations or other feeding points. Suitable circuit breakers must be installed at the points R_1, R_2, R_3, etc., and it is further clear that should a fault develop beyond the substation S S_2, although the fault current will be carried by all the cables between this point and the generating station, yet only those breakers which control the faulty feeder, namely R_4 or R_5, must operate.

Such discriminating action can be obtained, as is well known, by giving the various relays different time-lags. For example, R_2, R_4 and R_5 would have the shortest lags since the sooner a fault is cleared from the feeders which they control, the better. The time-lag of R_3 will be somewhat longer and that of R_1 longer still. In this way it is ensured that the breaker nearest to the fault will always come out first, thus reducing to a minimum the sections of the system which are shut down. The time interval between the operation of

* E. B. WEDMORE, *Transactions of the Institution of Mining Engineers*, 1910, vol. 38, part 2.

successive relays in series must not be less than that required for the opening of the breaker after the closing of the relay contacts, or the second breaker may commence to act before the first has isolated the fault. Modern switchgear may be relied upon to open the circuit within about one-fifth of a second or even less, but older gear will probably take considerably longer. To this time must be added that required for the relay to operate, as well as a margin for contingencies.

It may be assumed in general that intervals of $\frac{1}{2}$ second should be sufficient for quick-acting gear or $\frac{3}{4}$ second with less efficient patterns. Assuming $\frac{1}{2}$ second intervals, the relay settings for the system shown in Fig. 4 might be as follows :—

R_2, R_4, and R_5 ..	$\frac{1}{4}$ second
R_3	$\frac{3}{4}$,,
R_1	$1\frac{1}{4}$ seconds

To ensure that the consumer's breaker shall open first of all an extra $\frac{1}{4}$ second might be given all round.

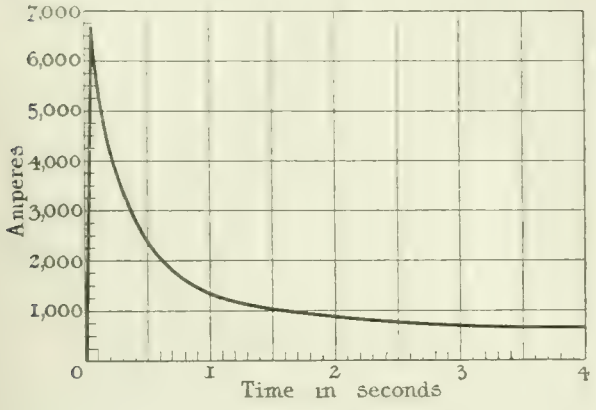

FIG. 5.—Short-circuit current of 4,000-kw. turbo-alternator.

In any case the respective circuit breakers will open from one-fifth to one-quarter of a second later than the times given above.

Such graded time-lags, when applied to overload relays, have a further very important advantage which does not seem to have received the attention it deserves. It is well known that although the short-circuit current of a modern alternator is comparatively small, probably not more than twice to three times its full-load current, yet the momentary current flowing into a short-circuit may be 10 times as great as the steady value. This is due to the fact that, whilst the steady short-circuit current is limited by a weakening of the field owing to armature reaction, the field necessarily dies away but slowly and, during the interval, the current is limited by resistance and inductance alone. Fig. 5* is a typical curve indicating the way in which the current rises to a maximum and then gradually falls to its steady value. Now in the case of a dead short-circuit occurring close to the generating station, it will be seen that if the breaker were to open instantly it would have to break a current nearly 7 times as heavy as if it opened after $1\frac{1}{4}$ seconds, as would be the case with the settings proposed above. The further from the generating station a fault occurs the more the short-circuit current will be reduced by the impedance of the intervening feeders, so that shorter time-lags can safely be given to the relays.

The question still remains as to whether the time-lags should be fixed * or inverse, i.e. independent of the magnitude of the fault current or an inverse function of it. It may be stated without fear of contradiction, that more interruptions of supply are caused by opening circuits prematurely than by leaving a fault on the system for too long a time. An interval of 2 seconds, however, should probably be regarded as the upper limit, and for substations containing synchronous machinery this figure must be considerably reduced. If fixed time-lags are employed they must be sufficiently short to deal adequately with short-circuits and, as a result, cables may be disconnected unnecessarily on the occurrence of small momentary overloads. For these reasons inverse time-lags are in every way to be preferred.

Fig. 6 gives the relative time curves of inverse time-lag overload relays of the induction type, set to operate with three different time-lags, to correspond with the values proposed for the relays of Fig. 4. It will be seen that for currents exceeding five times those for which the relays are set the time-lags reach an almost steady value, and it is this figure which should be taken as the criterion, and not the point at which the curve cuts the vertical axis, which is necessarily somewhat indefinite and, moreover, only applies to very small overloads. For this reason relays should invariably be scaled both in overload and short-circuit time-lags. It may be added that no relay can be considered satisfactory unless its time curve becomes practically horizontal at a moderate overload, otherwise the intervals between the operation of successive relays may become too short to allow of one breaker opening the circuit before that next behind it commences to act. It is, moreover, essential that the curves corresponding to different settings should follow one another closely throughout.

In both these respects the induction relay is much to be preferred to the fuse-shunted solenoid pattern. A fuse is, at best, a capricious piece of apparatus, and for a large distribution system to be dependent upon its vagaries seems to represent very doubtful economy. Solenoid relays with air dashpots are better, but for all important circuits the overload relays should undoubtedly be of the induction pattern with separately adjustable current and inverse time settings.

Whilst the time-lags suggested above, namely a maximum of $1\frac{1}{4}$ seconds, on the occurrence of a severe short-circuit near the generating station, are moderate, it may happen, in the case of a large number of relays in series or when it is necessary to allow much longer intervals between time settings on successive relays, that the delay on the relay at the generating station becomes excessive.

A simple method of overcoming this difficulty is based upon the following considerations.† The only case in which long time-lags are objectionable is when

* A. H. LAW : *Journal I.E.E.*, 1910, vol. 45, p. 344.

* Or "definite," as they are called in America.

† L. MURPHY : *Journal I.E.E.*, 1914, vol. 53, p. 172.

a fault occurs close to the generating station, for example, in the feeder between G S and S S_1 in Fig. 4. Should such a fault develop into a dead short-circuit between phases, it is essential to clear it with the least possible delay, the criterion of urgency being the extent to which the voltage is pulled down. A convenient means of applying this principle consists in arranging the tripping mechanism of the relays at R_1 (Fig. 4), and possibly at R_3 also, so that should the voltage fall to, say, 70 per cent of the normal, the time-lag is automatically shortened to perhaps half a second in each case. There is no objection to these two relays having the same time-lags, since it is hardly possible that both should simultaneously be subjected to a fault capable of pulling down the voltage to that extent. If there is any fear of this, the 70 per cent can be reduced to any desired extent. The same principle may be applied to all the relays, but when the time-lags are already short it presents no particular advantage.

The foregoing remarks refer more especially to the protection by means of fuses is usually advocated in addition, whereby simplicity is sacrificed and the instantaneous action which is generally put forward as a great feature of such systems is entirely lost.

It is to be observed that the leakage relay (L R in Fig. 3) takes the place of one of the three overload relays which would otherwise be required for pure overload protection, so that the adoption of leakage tripping does not involve any extra gear. In this connection it may be pointed out that the current transformers can be used to operate measuring instruments if necessary, but this practice is to be deprecated, not only because larger current transformers are necessary but also because there is considerable risk of the instrument circuits being interfered with for checking or other purposes, and it is most undesirable that the relay circuits should be disturbed in any way.

The current settings of the relays will necessarily depend upon the capacity of the feeder, as well as upon the load with which the individual breaker is capable of

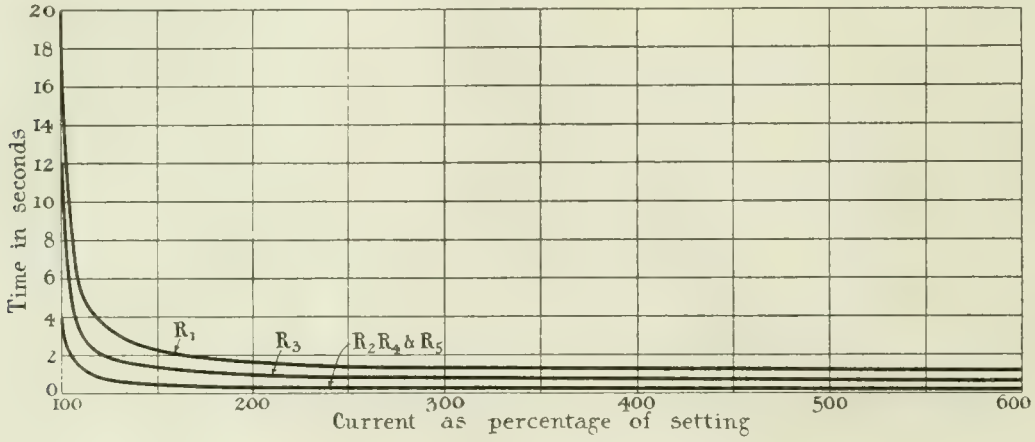

FIG. 6.—Time curves of induction type inverse time-lag overload relays.

overload relays (O R_1 and O R_2 in Fig. 3), but much the same considerations apply to the leakage relays (L R) except that, owing to the fact of the leakage current being definitely limited by the earthing resistance, there is no great advantage in cutting down the time-lag to a minimum. With leakage relays, likewise, there is nothing to be gained by the adoption of a fixed time-lag, although the objections to it may be less strong than in the case of overload relays.

This combination of leakage and overload relays has the important advantage that it is sufficient in itself to deal with faults at any and every point of the system, including the substation busbars, whereas many other methods such as the Merz-Price or the "split conductor," whilst excellent in themselves, act in watertight compartments, as it were, in that they only control individual sections of the feeders and afford no protection whatever to the substation busbars. Moreover, should one of the relays or circuit breakers fail to act, there is absolutely no second line of defence and the whole system is left at the mercy of the fault. For this reason, when balanced protection is adopted, overload dealing, since with a number of feeders in series, as in Fig. 4, the full-load currents will be progressively smaller the further the feeders are from the generating station. Although too much reliance must not be placed upon the grading of the current-settings as a means of discrimination, it has naturally an important bearing upon the question. As has been pointed out, the time curve of a relay should become nearly horizontal for currents exceeding, say, 4 times the setting (see Fig. 6). Consequently, if the short-circuit current exceeds this value in the case of all the relays through which it passes in series, each one will operate after the same lapse of time if they are all set for the same time-lag. On most systems, however, such a state of things is very unlikely, owing to the normal current at each succeeding substation being progressively less due to the load tapped off. Whilst, therefore, the minimum time necessary for the operation of the breakers should form the basis in arriving at the time intervals between the settings of the relays, nevertheless, a considerable reduction is nearly always possible owing to the discriminating effect of the current settings.

As an example of this, a large railway system near London may be cited as having in one case five sets of induction-type overload relays in series, each operating at 50 per cent above the full load of its feeder and set with an interval of only 1/10 second between their short-circuit time-lags. Several faults have occurred at different points and have, in each case, been cleared without any disturbance to the system. In this connection, it cannot be too strongly emphasized that for the effective operation of any system of protection, two things are essential: firstly, a knowledge of the short-circuit current liable to flow on the occurrence of a fault at any particular point of the system and, secondly, an understanding of the fundamental principles upon which the particular form of protection in use is based. No gear is fool-proof and no two distribution systems are precisely alike, consequently readjustments of time and current settings, as the result of experience, are always necessary and, if intelligently carried out, will often make the whole difference between success and failure.

The current settings of leakage relays necessarily depend upon the value to which the earthing resistance limits the fault current, and this question is discussed when dealing with the earthing resistances themselves. In the meantime it may be pointed out that since the

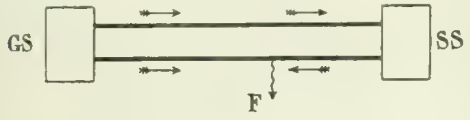

FIG. 7.—Parallel feeders.

current flowing through the leakage relay is the out-of-balance current of three current transformers (Fig. 3) it is important that the latter should have similar ratio curves. On the other hand, if the time-lags of the leakage relays are graded so as to give intervals at least as long as those of their corresponding overload relays, any want of balance, whether due to unequal distribution of current or differences in the current-transformer ratio curves, will be of small importance since such a want of balance is only detrimental in the event of a heavy *short-circuit* beyond the leakage relay in question, and this will be cleared as an overload before the out-of-balance current has had time to operate any leakage relay.

THE PROTECTION OF PARALLEL FEEDERS.

Fig. 7 shows a pair of parallel feeders running from a generating station (G S) to a substation (S S), one phase only of each feeder being shown for the sake of clearness. Suppose a fault to develop at F, current will be fed into it through both the faulty and the sound feeders, as indicated by the arrows, and the problem is to isolate the faulty feeder without interfering with the sound one. A very usual arrangement is to install reverse relays at the substation end of each feeder, on the assumption that the normal flow of power being from left to right, a flow from right to left necessarily implies a fault and would cause the appropriate relay to operate.

An objection to this arrangement is that if the cables are heavily loaded at the time, a high-resistance fault may not cause the current to reverse at all so that the feeder will not be isolated. In fact, with two parallel feeders, unless the current to earth exceeds the total load current at the moment, reversal cannot take place, and with three or more feeders the required excess will be still greater. This condition necessitates the installation of a larger earthing resistance than would otherwise

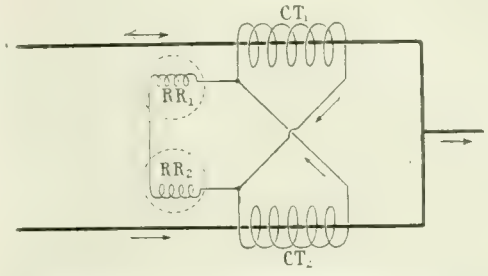

FIG. 8.—Differential reverse relay protection of a pair of parallel feeders. (Only one phase of each feeder is shown and pressure connections are omitted, for the sake of clearness.)

be necessary, thus throwing an undue strain upon all parts of the system owing to the heavier fault current.

This difficulty can be overcome by the use of differential reverse relays, the current connections for the substation end being shown in Fig. 8, the pressure windings being omitted for the sake of clearness. C T_1 and C T_2 are two current transformers, cross-connected in such a way that a flow of power in the direction indicated by the

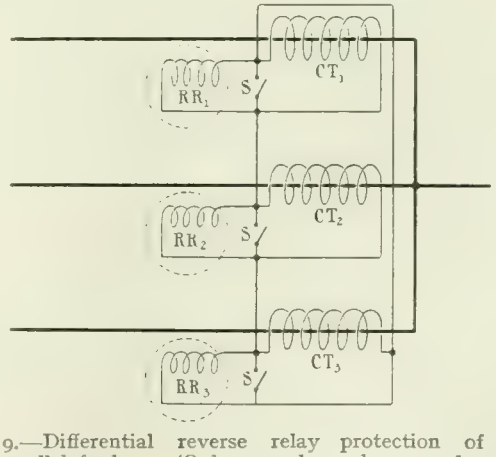

FIG. 9.—Differential reverse relay protection of three parallel feeders. (Only one phase shown and pressure connections omitted, for the sake of clearness.)

arrows merely causes a circulation of current in the secondaries, and none flows through the relays R R_1 and R R_2 which are connected in series between equipotential points. On the occurrence of a fault, the currents in the two feeders are no longer equal and the difference current flows through the reverse relays which are so arranged that one or the other operates, according to the direction of the current through them, and thus isolates the faulty feeder alone.

Since the relays operate with a given difference current, it is immaterial whether there is actual reversal or not; in fact the difference current is always equal to twice the leakage current flowing into the fault through the substation. A further important advantage possessed by this arrangement, as compared with simple reverse relays, is that a surge producing a simultaneous reversal of current in both feeders will not cause either relay to operate. Such a reversal may well occur, particularly with rotary substation machinery, when a secondary fault is suddenly cleared by the opening of a low-tension circuit breaker.

In the case of four or six parallel feeders, they can be very simply arranged in pairs and with three such feeders the connections shown in Fig. 9 are applicable. Normally, all three feeders carry approximately equal currents. In the event of any variation in the currentin

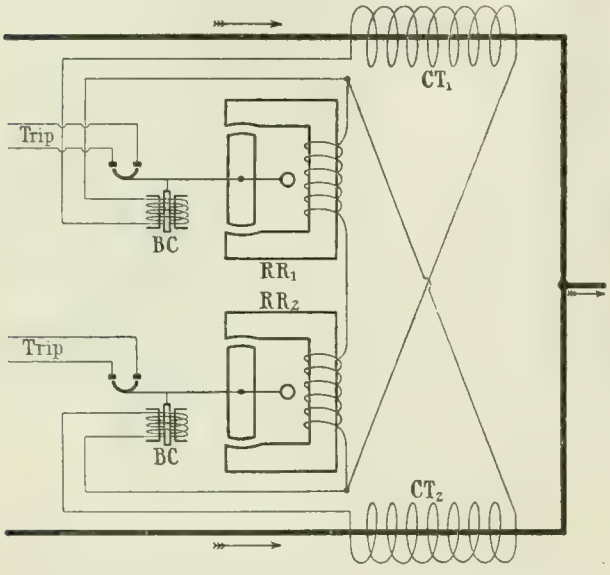

FIG. 10.—Pair of parallel feeders protected by biased differential reverse relays. (Only one phase shown and pressure connections omitted, for the sake of clearness.)

one of them, due to a fault, the difference-current flows through the corresponding relay and causes it to operate. As soon as this has occurred, and the faulty feeder has been disconnected, the dead current transformer and its relay merely represent useless impedance and reduce the sensitiveness of the remaining two relays. To obviate this a switch (S) should be provided which is automatically closed by the circuit breaker as it comes out, so that the current transformer is short-circuited and the connections of Fig. 9 become equivalent to those of Fig. 8.

At their outgoing ends, parallel feeders present much the same problem as a single feeder and may be similarly dealt with by means of combined overload and leakage trips, a group of relays as shown in Fig. 3 being applied to each feeder. If this is done, graded time-lags must be applied to both the overload and leakage relays, on the principles already indicated. If the fault occurs close to the substation the fault current may divide itself almost equally between the two feeders and, under these conditions, there is a risk of the sound feeder coming out instead of the faulty one. Morever, after the latter has been isolated at the generating station end the fault current will still flow into the sound feeder and may cause its relay to operate. For these reasons it is preferable to install differential reverse relays (Figs. 8 or 9) at the outgoing end as well as at the other. Besides ensuring the isolation of the faulty feeder alone, this arrangement has the advantage of uniformity. It will be seen from Fig. 7 that, at the substation end, the fault current flows in opposite directions through the two current transformers so that the effect upon the relays is doubled, and for this reason the settings may be low, with the corresponding advantages of leakage protection.

If the relays at the outgoing end have isolated the faulty feeder before those at the substation the fault current will flow into the sound feeder, and as it then forms the out-of-balance current it will operate the relay and isolate the sound feeder as well. To prevent this, the circuit breaker on each feeder should be fitted with an auxiliary contact which, in coming out, renders inoperative the relay on the opposite feeder. At the substation end this is unnecessary since after the breaker has acted the out-of-balance circuit flows in such a direction as to hold the other relay open.

Apart from the fact that a reversal will cause its

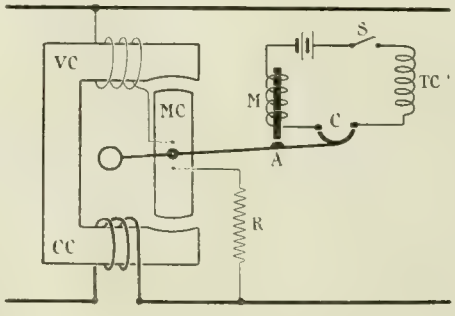

FIG. 11.—Reverse relay compensated for voltage.

relay to act, the sound feeder is left without protection. To remedy this, overload relays may be added or the reverse relays can be rendered operative on a heavy forward current. The relay shown in Fig. 11 can be arranged to act with such a current if the pressure circuit is opened, which can readily be done by means of an auxiliary switch operated by the circuit breaker as already described. It must not be forgotten that the whole load current now forms the out-of-balance current and it is therefore essential that the relay windings should be capable of carrying it without overheating. Failing this, the relays must be cut out of circuit by the auxiliary switch, separate overload protection being provided at the outgoing end.

If there are a number of parallel feeders in series, laid out, for example, on the lines of Fig. 4, perfect discrimination is afforded by the arrangement described, the reverse relays being only operative in the case of faults in the particular lengths of cable which they

control, so that no discriminating time settings are necessary and the problem becomes a simple one.

If a pair of feeders is connected to the busbars through transformers the relays may be connected on the secondary side so as to isolate the transformer as well as the feeder. In the case of reverse relays it is often recommended that the potential coils should be fed from the primary side of such a transformer so as to minimize the effect of a fall of voltage in the event of a severe secondary fault. This is advisable, if it can conveniently be done, but with a relay having the characteristics shown in Fig. 12 it is not, by any means, essential. Another consideration which enters into the question of whether the relays should be fed from the primary or secondary sides of such a transformer is, that if it steps down from an exceedingly high pressure to a moderate one, the cost of the transformers is much reduced if they are connected on the lower voltage side. It should be pointed out that if the power transformer in question is connected delta-star or star-delta there will be a phase displacement of 30° between primary and secondary which must be corrected in the relays. This is readily done by changing the connections of the pressure windings from star to delta or vice versa, it being noted, at the same time, that there is a corresponding change in the value of the voltage applied to each relay, which must be allowed for. It may be observed that transformers protected in this way do not run the risk of being isolated through an abnormal rush of magnetizing current when first switched in, as may occur with Merz-Price transformer protection, for example.

It has so far been assumed that, under normal conditions, the currents in all the parallel feeders are equal. If the cross-sections of the feeders differ, the current transformer ratios should be so chosen that when the feeders are running in parallel, the secondary currents of the transformers are equal. Moreover, it is important that the currents should distribute themselves correctly between the two or more parallel feeders and that the current transformers should have similar ratio curves and phase displacements. If these points are not attended to there is a risk of the relays on sound feeders acting, owing to a fault beyond them. A little consideration will show, however, that the effects of a slight lack of balance are not, in practice, so serious as might at first sight appear, so long as similar inverse time-lags (however short) are given to all the relays, since those on the sound sections will only tend to operate by reason of such want of balance, whereas the relays controlling the faulty feeder will be influenced by the whole fault current and will therefore come out first. In any event it is only one feeder of the pair which is disconnected, so that no great harm will be done.

Various methods have been suggested for giving the necessary "bias" to the relays of Figs. 8 or 9, so as to prevent any unavoidable want of balance from causing trouble in this way. Merely to increase the current setting is not a solution, since with a heavy short-circuit amounting, as it well may, to 100 times the full-load current a want of balance of 5 per cent will involve an out-of-balance current through the relays of five times full load, and is therefore bound to be many times greater than that necessary to operate them. What is required is that the bias, instead of being constant, should increase with the current in the feeders; that is to say, the bias should represent a definite percentage of the current flowing.

A method of carrying this into effect is shown diagrammatically in Fig. 10. R R_1 and R R_2 are a pair of reverse relays, fed by current transformers C T_1 and C T_2, cross-connected as in Fig. 8. Besides the usual fixed control which gives a definite current setting to each of the relays, a biasing coil, B C, applies an additional control which is proportional to the current flowing in the feeders. If this auxiliary control is such as to give a bias of 5 per cent or at most 10 per cent, it will cover all likely contingencies as regards want of balance. It is usually desirable that the bias should increase more than in proportion to the current, since unbalancing is often more pronounced at heavy overloads.

In the case of substations fed by a large number of parallel feeders, or from two sources by independent pairs of such feeders, it may sometimes be possible to treat a pair as a single unit and to isolate both on the occurrence of a fault in either. If this is permissible the two reverse relays in Fig. 8 can be replaced by a single overload relay controlling the circuit breakers in both feeders.

Requirements of a Reverse Relay.

It is of fundamental importance in the case of all protective systems involving reverse relays that the latter should operate with certainty even if the voltage of the system is pulled down to a small fraction of the normal. The usual reverse relay consists of a watt-meter movement provided with a pair of contacts, so that, at a given power factor, the current required to actuate it is inversely proportional to the voltage. For example, should the latter fall to 5 per cent of the normal, the current will have to rise to 20 times the setting before the relay will act. To get over this difficulty such relays are usually set so as to operate with 10 per cent, or even less, of the normal full load so that, under the conditions assumed above, the relay would trip with twice the full-load current. Such an arrangement might seem quite rational since there is no difficulty whatever in designing a sufficiently sensitive relay. But to set it to act at such a low current is to court disaster, seeing that momentary reversals amounting to considerably more than 10 per cent are bound to occur in practice, and for a circuit breaker to be tripped under such conditions is fatal.

The only true solution, therefore, is to render the reverse relays, as far as possible, independent of a fall in voltage, and the working principle of a well-known form of such relay is shown in Fig. 11. It is a moving-coil instrument having an iron circuit carrying two fixed windings, a current coil (C C) and a volt coil (V C), so connected as to assist one another with a forward current and to oppose one another with a reversal. The moving coil (M C) is connected in series with V C and a non-inductive resistance (R) between phases or to the neutral point, according to circumstances. The windings V C and C C being in opposition under operating (reverse) conditions, the flux in the air-gap

for a given current increases rapidly as the pressure falls and thus largely compensates for the reduced current flowing through the moving-coil winding.

Fig. 12 shows how successfully this result is accomplished. It will be seen that a relay set to operate at 25 per cent of full load, under normal voltage conditions, will only require twice full-load current to actuate it, even should the voltage of the system fall to 2 per cent of the normal. Such a result puts the reverse relay upon an entirely different footing and removes

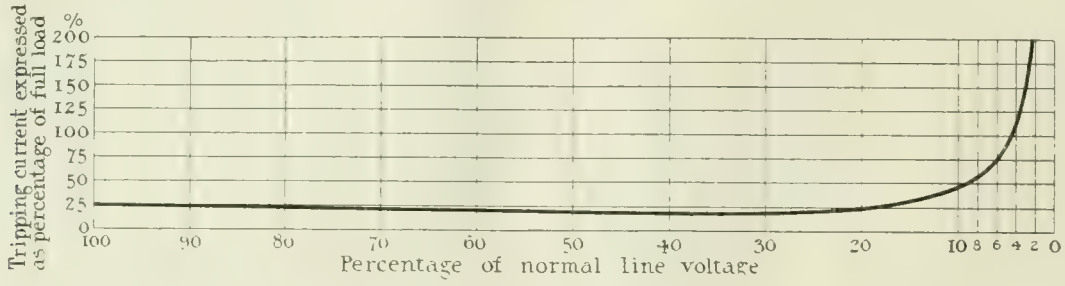

FIG. 12.—Curve showing current required to operate the relay of Fig. 11, under low-voltage conditions.

the objection which was at one time so often raised. This form of relay, moreover, can be designed to operate with an exceptionally heavy forward current (say 20 times the setting) at zero voltage and, as has been seen, this is sometimes a useful feature.

It must not be forgotten that in the case of a fault between two lines only, the fall of voltage will not be the same on all three phases and a seriously distorted voltage triangle will result. In Fig. 13 the normal

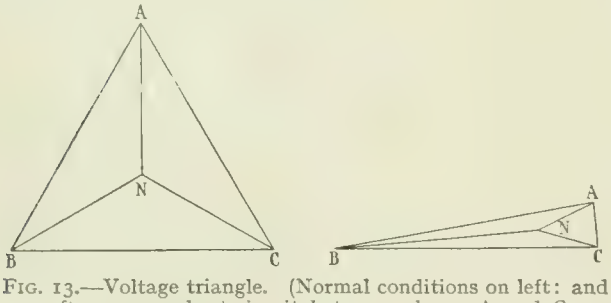

FIG. 13.—Voltage triangle. (Normal conditions on left: and after severe short-circuit between phases A and C, on right.)

voltage triangle is shown on the left, whilst on the right is seen that resulting from a severe single-phase short-circuit between phases A and C. As usually connected, the pressure winding of the reverse relay whose current coil is in phase A would be joined between A and an artificial neutral point N. Under normal conditions, with a non-inductive load, the current and pressure are in phase with one another and are each represented in direction by A N. Under the short-circuit conditions, as represented by the right-hand figure, the current A C and the pressure A N are seen to be almost 90° out of phase with one another and, consequently, the relay will require an unlimited current to operate it, quite apart from any effect which the reduced value of the phase voltage may have upon its operation. If, on the other hand, the fault occurs between phases A and B the vector will swing nearly 90° in the opposite direction.

A simple method of getting over this difficulty, due to Mr. E. B. Wedmore, consists in connecting the pressure winding between B and C, when the current winding is, as before, in phase A. Under normal conditions at unity power factor the current and pressure will be 90° out of phase and a corresponding phase displacement is introduced into the relay windings so as to bring the current and pressure fluxes into phase. Under the short-circuit conditions shown in the right-hand figure the current (A C) and pressure (B C) are seen to be still practically 90° out of phase. In fact the greatest departure from this displacement occurs in the case of a moderate fault between the two phases, when it falls to 60°. The maximum deviation from the mean position under all possible conditions is, therefore, only 15° in either direction. Moreover, the voltage between B and C is but little reduced compared with that to the neutral (A N). With three-core cables a short-circuit between two phases which does not at once spread to the third phase is almost an impossibility, but on overhead lines it is one of the commonest of faults, besides being by no means unknown in circuit breakers and busbars, and in all cases where a severe single-phase fault is liable to occur the relay connections just described should be adopted.

Allusion may be made to an extensive overhead system working at 20,000 and 100,000 volts which suffered from a series of shut-downs due to lightning and on which various systems of protection were tried and found quite ineffective. Compensated differential reverse relays as just described were then installed and proved successful in every possible way; in fact, it is not too much to say that they saved the situation under most trying conditions.

The contact-making arrangement of the relay, shown in Fig. 11, may be worthy of mention. As soon as the contacts close at C a current flows through the breaker trip coil (T C) in series with the small magnet (M) which is thereby energized and by attracting an armature (A), carried by the contact arm, draws the latter up firmly, thus ensuring continuous and effective contact. With this arrangement, carbon contacts are employed instead of the more delicate tungsten, platinum or mercury. The circuit breaker should

be so arranged that, in coming out, it opens a switch (S) and thus releases the contact arm so that the relay resets itself automatically. This auxiliary switch is essential in all cases, since it is most undesirable that the circuit should be broken at the relay contacts.

PROTECTION OF INTERCONNECTORS AND RING MAINS.

In these the normal flow of power may be in either direction, according to the distribution of the load at the moment. The case of two generating stations, G S_1 and G S_2 (Fig. 14), connected by a single interconnector (upper figure) presents no difficulty, overload protection at each end being all that is required. If the feeders are parallel (lower figure) the differential reverse relays of Fig. 8 or Fig. 9, installed at each end, will meet the case. The arrangement already described for preventing the operation of the relays on

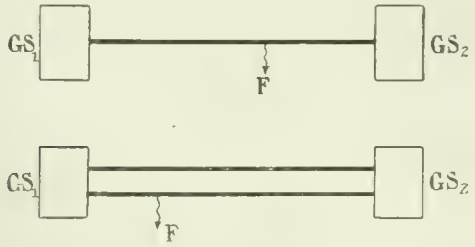

FIG. 14.—Feeders interconnecting two generating stations.

the sound feeder after the faulty one has been isolated is, of course, essential.

The ring main in Fig. 15 presents a more difficult problem. The interconnector between the substations S S_1 and S S_2 cannot be controlled by overload relays since it may carry an overload due to a fault between the generating station and S S_1, for example. Nor can reverse relays be used, since the flow of current may be in either direction under quite normal conditions. A simple solution is, however, possible on the following

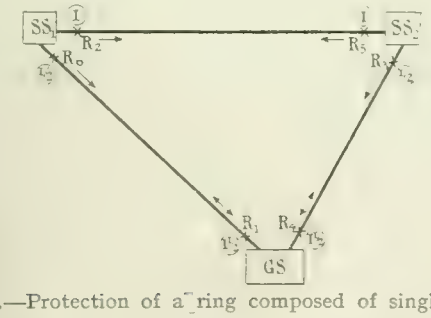

FIG. 15.—Protection of a ring composed of single feeders.

lines. If the ring were open at R_4, power would, under all conditions of load or faults, flow in a clockwise direction, and overload relays with discriminating time-lags installed at R_1, R_2 and R_3 would afford the desired protection, in precisely the same way as with independent feeders. If, on the other hand, the ring were open at R_1 the flow of power would always be in a counter-clockwise direction and overload relays with discriminating time-lags could be installed at R_4, R_5 and R_6. If, now, the ring be completely closed the following conditions hold good, no matter on which section the fault occurs :—

(1) The fault current will always flow through R_1 and R_4 in an outward direction.
(2) The relays R_2 and R_3 should be responsive to a clockwise flow of power alone.
(3) Relays R_5 and R_6 should be responsive to a counter-clockwise flow of power alone.

If, therefore, overload relays are installed at R_1 and R_4 with reverse relays at R_2, R_3, R_5 and R_6, they can all be so set as to be inoperative except under fault conditions. In Fig. 15 the arrows show the direction of flow to which the various relays should be responsive and the figures in circles indicate suitable short-circuit time settings, on the assumption that a minimum interval of half a second is required between successive relays.

Fig. 16 shows a more extensive system, involving a ring main, four substations and two generating stations.

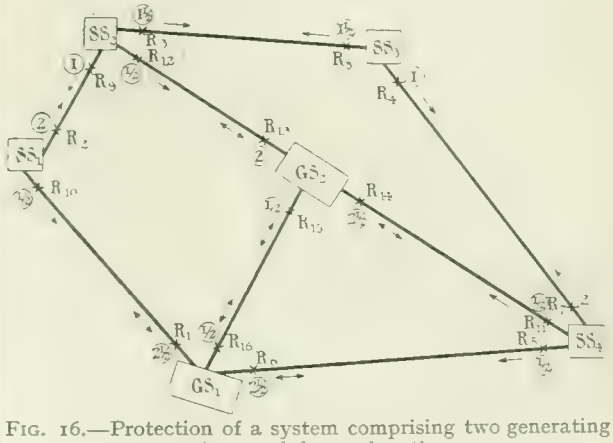

FIG. 16.—Protection of a system comprising two generating stations and four substations.

In this case relays R_2, R_3, R_{12}, R_4 and R_5 are arranged to be responsive to a clockwise flow of power, while R_7, R_{11}, R_8, R_9 and R_{10} respond to a counter-clockwise flow, and R_1, R_6, R_{13}, R_{14}, R_{15} and R_{16} may be pure overload relays. As before, the respective directions are indicated by arrows and appropriate short-circuit time-lags are shown by the figures in circles.

It will be noticed that the time settings of relays R_1, R_2, R_6, R_7, R_{13} and R_{14} are somewhat long and, although in most cases they might very probably be reduced owing to the discrimination afforded by the current settings, in other cases the times might even have to be increased if the circuit breakers were slow in action. To avoid leaving a heavy short-circuit on the system for so long a time, the arrangement already described whereby, should the voltage fall to a predetermined value (say 70 per cent of the normal), the time settings are reduced to a lower figure, may usefully be applied to these four relays. By accelerating the time-lags by one second in this way, the maximum possible interval during which a short-circuit could be held would be 1½ seconds.

The reverse relays should, of course, be such as to be unaffected by a fall of voltage, and it is a great advantage, for the reasons already gone into, for the relays to be responsive not only to overloads but also to leakage.

Fig. 17 shows such an arrangement.* The relays R_1 and R_2 have their current and potential windings connected to phases 1 and 3 respectively, and will consequently respond to overloads or to short-circuits between any of the phases. The leakage relay (L R) has its current winding in the common return of the current transformers and is provided with three pressure windings each fed from one of the single-phase potential transformers T_1, T_2 and T_3, the primaries of which are connected in star and earthed. If the insulation of the three mains is perfect, the potential transformers will have equal voltages applied to their primaries and the resultant flux due to the leakage relay

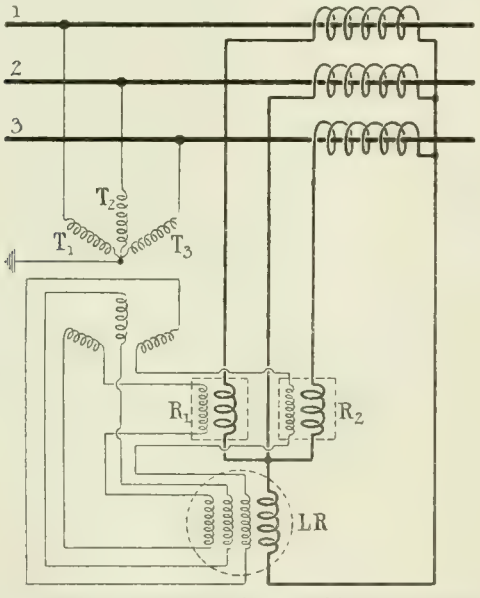

Fig. 17.—Feeder protection by combined overload and leakage reverse relays.

pressure windings will be zero. If, however, phase 3, for example, goes to earth, transformer T_3 will have a reduced voltage applied to it, whereas that of T_1 and T_2 will be increased. As a result, the balance will be upset and there will be a resultant pressure flux in L R in phase with the voltage between line 3 and earth. The leakage current will also be practically in phase with this voltage and will therefore cause L R to operate. By this means, relays R_1 and R_2 will deal with overloads whilst relay L R deals with a leakage to earth, and each relay discriminates correctly as regards direction. With such reverse and leakage relays at the substation ends of the feeders, overload and leakage relays (as in Fig. 3) may be employed at the generating station ends, but it is often preferable for the sake of uniformity to employ the same relays throughout and the connections of Fig. 17 are equally applicable to the outgoing ends.

* See also Patent No. 8569 of 1912 (E. B. Wedmore).

In many cases the interconnectors forming the ring may be run in parallel and, in that case, a simple solution is afforded by the use of the differential reverse relays* shown in Figs. 8 or 9, as the case may be. A moderate time-lag of, say, $\frac{1}{2}$ second will be found sufficient for all the relays, since they are inoperative except against a fault in the particular feeder which they control. At the generating station ends pure overload relays may be substituted for the differential reverse relays, since the flow of power is always in the same direction at these points, but it is usually more convenient to employ the same type of relay throughout, and exact discrimination is thereby more easily obtained.

It is important to distinguish between the functions of the relays at the respective ends of the parallel feeders. Referring to Fig. 7, it will be seen that at the outgoing end the faulty feeder carries the larger current, since the fault current is in the same direction as the load current, upon which it is superposed. At the incoming end, however, the fault current flows in the reverse direction through the faulty feeder, which consequently carries a smaller current than the sound one. The relays, at the outgoing end, therefore, have to isolate the more heavily loaded of the two feeders and at the incoming end the more lightly loaded.

In the case of an interconnector or a ring main the flow of energy may be in either direction, so that the relays at each end must be able to exercise the one or the other function according to the direction of flow. The only relays capable of this are those in which the sense of direction is given by a pressure winding. Relays having current discrimination only can be arranged to cut out *either* the more or the less heavily loaded feeder but are incapable of performing both functions and are therefore useless for the protection of interconnectors or rings.

It is the custom on many systems to run with the ring open at some point, and it may be observed that the arrangements proposed for single and parallel rings are equally effective under these conditions. It is, of course, clear that if the ring is permanently open at some point it ceases to be a ring and the overload protection recommended for the lay-out of Fig. 4 is applicable. Seeing, however, that it may at any time become necessary to close the ring, it is very undesirable to rely upon overload protection in such cases.

It will be observed that with differential reverse relay protection at both ends of parallel feeders the substation busbars are unprotected. To remedy this, minimum voltage relays may advantageously be installed at each substation, and set to operate should the voltage fall to, say, 50 per cent of the normal, thus causing the breakers on the feeders on either side of the faulty substation to open and so to isolate it.

Connections to Consumers.

In the case of large consumers, the connections amount to what is practically a substation and can be dealt

* Since in the case of interconnectors the flow of power may be in either direction, even under healthy conditions, relays used in this way might be more correctly described as "directional relays"—following the American practice—rather than as "reverse relays."

with accordingly. In other cases, the consumer may be merely tapped off a feeder and the consumer's installation should then be controlled by overload or, better still, by combined overload and leakage relays (Fig. 3) with very short time-lags.

A more difficult problem arises when a consumer is tapped off a pair of parallel feeders and is able to take power from either feeder at will. In such a case protection of the ends of the parallel feeders by differential reverse relays (Fig. 8) is inadmissible since the consumer's demand unbalances the load between the two feeders.*

Protection of Generators and Transformers.

The protection of generators and transformers is somewhat outside the scope of the present paper, except in so far as transformers can be regarded as forming part of a feeder and may then be protected in the way already described. In many other cases transformers can be protected as part of a generator, motor, etc.

The protection of generators must be touched upon owing to the effect which it has upon the current capacity of the earthing resistance. Various excellent systems are available for the protection of generators, one of the latest being the Merz-Beard in which the two ends of each generator winding are led through a ring transformer to the secondary of which a relay is connected. A fault between phases or to earth causes an inequality in the currents, and if this is sufficiently great the relays will operate. Should an earth fault develop towards the neutral point end of the winding the voltage will be small, and in order to ensure the operation of the relay the ohmic value of the earthing resistance must be kept much lower than would otherwise be necessary, with the result that many of the advantages of leakage tripping are lost.

The reverse relay, compensated for voltage, forms one of the simplest and most direct methods of generator protection. The criterion of whether a generator should be removed from the busbars or not is presumably whether it is still in a position to supply power to the system or is actually taking power from it. This latter condition may arise, either from an internal short-circuit, an earth, loss of field, or a fault in the prime mover. Loss of field or failure of steam does not usually involve a sufficient reversal of power to make immediate removal from the busbars imperative, but other faults in the prime mover, such as the seizing of a bearing, undoubtedly do so. Most isolating devices, the Merz-Price or Merz-Beard, for example, are only sensitive to an earth or a fault between phases and will not operate on the occurrence of a short-circuit between turns, or a mechanical breakdown, or a mistake in paralleling. A reverse relay, on the other hand, will operate under all fault conditions.

The fear is sometimes expressed that a heavy cross-current, whether due to bad paralleling, hunting of the generators, or a fault elsewhere on the system, may bring out the generator breaker if controlled by reverse relays. Experience shows, however, that with reasonable current settings and a time-lag of a fraction of a second, such fears are quite groundless. It may be pointed out that although the circulating current between the machines is often considerable, it is very much out of phase with the voltage and consequently has little tendency to operate the relays. On the other hand, if an actual mistake is made in paralleling and a generator is connected to the bars either when dead or when out of phase, the relay will act and prevent damage.

In a number of stations, generators are still "protected" by means of overload relays. It is then a matter of pure chance whether the faulty or a sound generator is removed from the bars. If only two machines are running at the time it will certainly be the sound one; if there are a number running there may be some hope of its being the faulty one which is cut off. Since existing current and potential transformers can in almost all cases be used, the change from overload to reverse relay control should most certainly be made.

As has been pointed out, certain patterns of reverse relay can be arranged to operate with an exceptionally heavy forward current accompanied by a fall of pressure. In the case of generator relays this affords a means of isolating the generator in the event of a serious busbar fault.

It is important, whatever system of protection is employed, that the field of the faulty generator should be broken immediately the machine has been taken off the bars, otherwise the stator will inevitably be destroyed owing to the heavy fault current. It is usually considered inadvisable for the relay itself to perform this operation since, in the possible event of a failure of the breaker to open, the machine will be left on the bars without its field. On the other hand it is arguable that quite as much damage might be done to the machine if it were pumping current into the fault under full excitation. In fact, in the author's opinion it is of even greater importance that the field should be promptly opened than that the generator should be removed from the bars, and the simplicity of having the trip coils of the field breaker and main breakers in series across the relay contacts has much to recommend it. If the relay is not to operate the field switch, the main breaker must do so in coming out and subsequently open the tripping circuit so as to reset the relay. The circuits must, moreover, be so arranged that if the main breaker is tripped by hand the field is not opened.

Typical Protection Diagrams.

In Figs. 18 and 19 are shown a number of typical feeders, etc., with the method of protection recommended for each. The points at which circuit breakers and relays are required are marked by a cross, and against each is given the number of the figure in which will be found a connection diagram of the protective device recommended. Practically every system can be divided up into elements such as those shown and the whole dealt with in the way proposed.

Methods of Earthing the System.

The question has now to be considered of the best method of connecting the generator neutral to earth through its limiting resistance. It is usually

* An arrangement which meets this difficulty is described in the author's reply to the discussion (page 414).

possible to connect the neutral points of all the generators to a common bar which is earthed through a resistance. A possible disadvantage of this arrangement is that

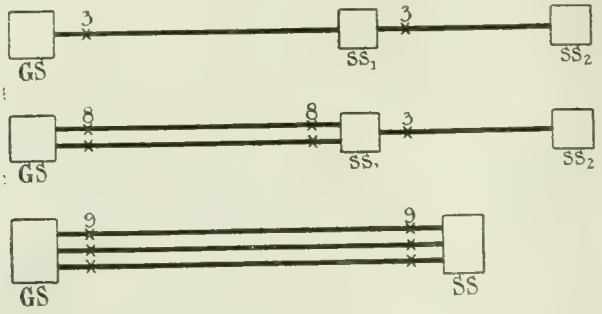

FIG. 18.—Protection of independent feeders. (The numbers are those of the corresponding figures in the text.)

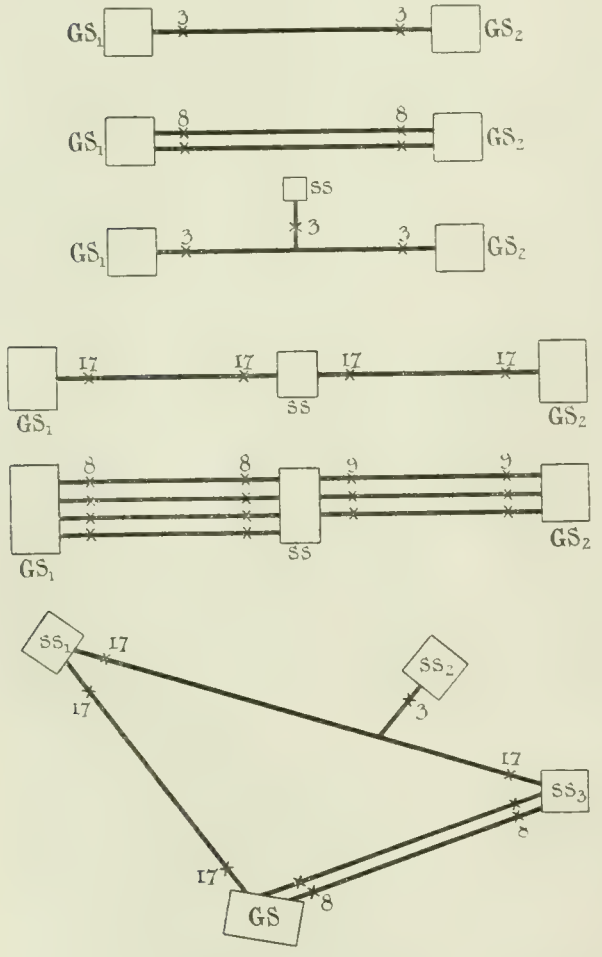

FIG. 19.—Protection of interconnectors and rings. (The numbers are those of the corresponding figures in the text.)

if the triple harmonic of the wave-form is very pronounced a current will circulate between the machines. The heating effect of this current is not serious, in fact a triple harmonic current equal to as much as half the full-load current of the generator will increase its copper loss by less than 3 per cent. At the same time, such circulating currents may be objectionable in their effects upon measuring instruments, etc., and should this prove to be the case they can be eliminated either by earthing only one generator at a time or by connecting a part of the resistance between each neutral point and the earthing bar, as shown in Fig. 20. If the resistances R_1 and R_2 are each made equal to about 15 per cent of R_3, the triple-frequency current will usually be reduced to perfectly negligible dimensions or, of course, a separate earth resistance can be provided for each generator. If a common resistance is provided, a switch must be inserted in each earth connection so that dead generators

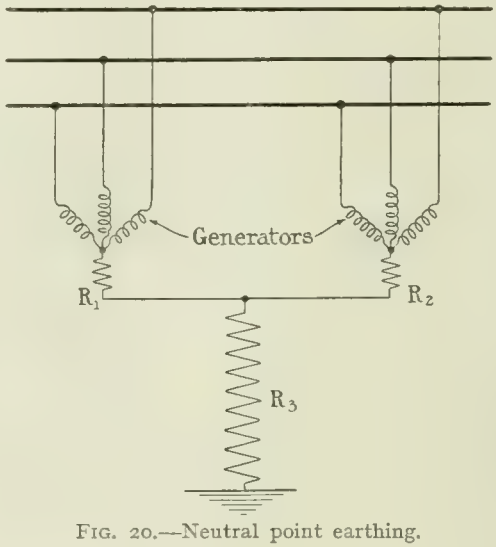

FIG. 20.—Neutral point earthing.

can be disconnected from the earthing bar. If this is not done the dead generators will be "charged" in the event of a fault on the system.

If it is desired to benefit by leakage protection on systems in which the neutral point is not available—those involving delta-wound generators or transformers, for example—it becomes necessary to form an artificial neutral point. Resistances or choking coils, star-connected to earth, will not meet this requirement since no current flows through the fault in the event of one phase of the system going to earth. The best arrangement is probably a zig-zag connected three-phase transformer as shown in Fig. 21. Each limb carries two similar windings connected in adjacent phases, one end of each being starred and the remaining ends connected, through earthing resistances (E R), to the lines. The small figure on the right shows the relative phase relationships of the six windings. Under normal conditions the current taken is merely the magnetizing current of the transformer, but should an earth develop, for example on the lower phase, a voltage is induced in the windings connected between the faulty phase and earth on limbs 1 and 2 by the other two coils, which are connected to healthy phases. The current flowing to earth through the

fault may be limited by the earthing resistances to any desired value. This arrangement is in use on some large plants in the United States and has proved very satisfactory.

Forms of Earthing Resistance.

A common form of earthing resistance consists of metal grids so connected in series and parallel

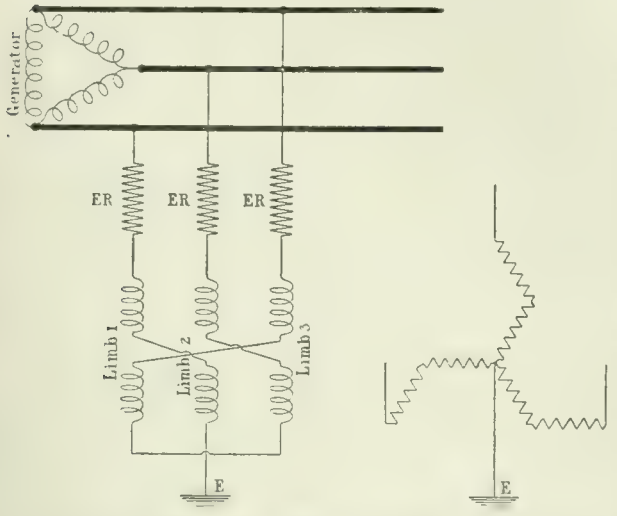

Fig. 21.—Delta-connected generator earthed through zig-zag connected transformer.

as to give the required ohmic resistance and current-carrying capacity. Such grids have a high temperature coefficient so that the current passed may fall to half its initial value after some 15 seconds. From this it follows that when time-lags are fitted to the relays the initial resistance must be made abnormally low in order that it may pass a sufficient current, after

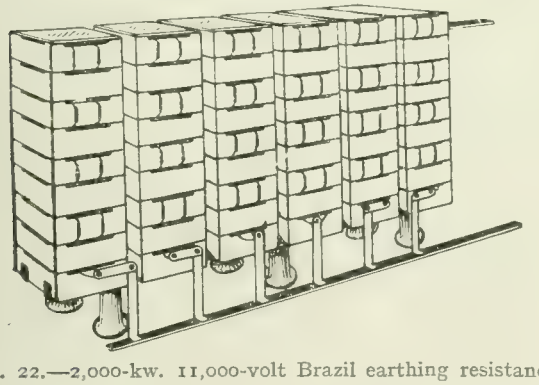

Fig. 22.—2,000-kw. 11,000-volt Brazil earthing resistance.

the lapse of a given time, and still allow a reasonable margin of safety. If, on the other hand, the earthing resistance has a negative temperature coefficient the current will gradually increase in value, the initial current being reduced to a minimum, so that, by this means, the low ohmic resistance required to deal with a high resistance fault is obtained without its being necessary to raise the initial current. As has already been pointed out, the initial short-circuit current of a generator is many times its stationary value and, consequently, it is of considerable advantage to have a resistance which is a maximum at the outset, subsequently falling in value so as to equalize the current rush to some extent.

An earthing resistance possessing these features is the carbon-powder pattern due to Mr. Brazil, which consists of a number of fireclay troughs containing the powder between carbon terminals. The troughs are mounted one above the other and grouped as may be necessary to give the required resistance and current-carrying capacity. One of a pair of such resistances, installed at the London and South-Western Railway Company's generating station and each designed to

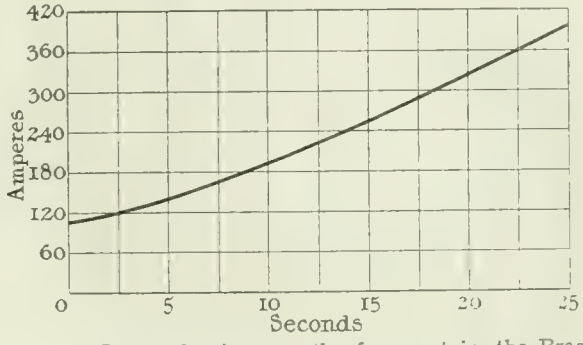

Fig. 23.—Curve showing growth of current in the Brazil earthing resistance illustrated in Fig. 22.

pass 325 amperes at 11,000 volts, after 20 seconds (2,000 k.v.a.), is illustrated in Fig. 22. Fig. 23 shows how the current passed gradually increases from 105

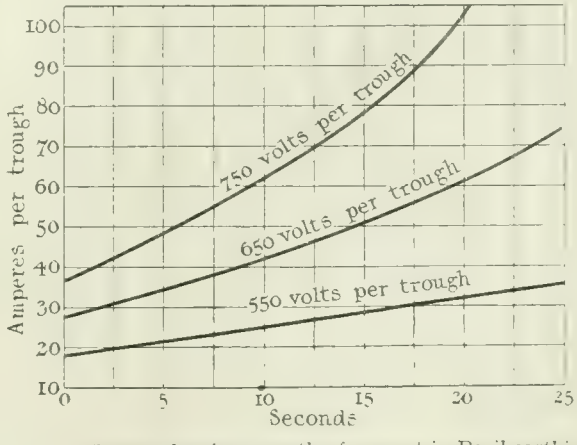

Fig. 24.—Curves showing growth of current in Bazil earthing resistances.

amperes at the start to 190 amperes after 10 seconds and 325 amperes after 20 seconds.

The flexibility of such resistances will be gathered from Fig. 24, in which the curves indicate the growth of current in a single unit when 550, 650 and 750 volts, respectively, are applied to its terminals. The increase of current during a given time is roughly proportional

to the square of the applied voltage; and by choosing still lower terminal voltages, resistances can readily be designed capable of being left in circuit for an indefinite period, but in modern practice this is seldom called for. With such a resistance, a dead earth, even on or near the busbars, will at no time allow the current to exceed that which is necessary to operate the relays, so that not only is the shock to the system reduced to a minimum but the breaker opens the circuit at minimum current.

The Brazil resistance, consisting as it does of fireclay troughs, carbon powder and carbon terminals, may be regarded as practically indestructible, both as to burn-outs and to insulation breakdowns, and can even be run red hot for an indefinite period, if need be, without danger. It is, moreover, extremely compact. The resistance illustrated in Fig. 22 designed, as has been said, to deal with 2,000 k.v.a. at 11,000 volts, only measures 56 in. × 28 in. × 26 in. overall. As will be seen, no particular precautions are necessary as regards its installation, and an important feature of the construction lies in the ease with which the units can be re-grouped or extended at any time to meet future requirements. For example, if it is found that connecting the generator neutrals to a common bar gives trouble from triple-frequency currents, it is a simple matter to re-group the units on the lines of Fig. 20.

Earthing through Reactances.

In lieu of a resistance in the earth circuit the use of a reactance has been proposed, but such an arrangement suffers from serious disadvantages. In the first place the potential difference at its terminals is nearly 90° out of phase with the current flowing through it, so that the neutral point is raised to a very much higher potential above earth than would otherwise be the case. For example, an earth fault which with a non-inductive earthing resistance would raise the neutral point to 50 per cent of the phase voltage above earth will, if a reactance is used, increase its potential to nearly 90 per cent of that voltage, thus very greatly increasing the strain upon the system without introducing any corresponding advantage.

A still more serious objection to be urged against a reactance lies in its effect upon surges and oscillations. A non-inductive resistance connected between the neutral point and earth has proved a most potent factor in damping out over-pressures, whether due to internal or to atmospheric causes. A reactance, on the other hand, not only does not damp them out but may form, with the capacity of the system, an oscillatory circuit of its own. Under ordinary conditions of working the self-induction of the generator windings is much too low to give resonance at the frequency of the system, and artificially to increase the inductance is therefore most inadvisable. The question of resonance was very fully gone into by the late Mr. Duddell in his 1913 Presidential address,* and in this connection he says: "Summing up, it may be said that resonance at the fundamental frequency is rare, but very dangerous when it does occur." It might be thought possible so to calculate the value of the reactance that resonance could not occur, but it will be clear that the capacity of the system is a variable quantity, depending upon the number of feeders in use at the time, and, moreover, it is not only resonance with the supply frequency or its harmonics that has to be feared but also sudden changes of current, steep-fronted waves, sparking contacts, arcs, and so forth, none of which phenomena is amenable to calculation. Against these a reactance is powerless since it cannot damp out a wave, as does an ohmic resistance, but merely reflects it back into the system, usually with a rise of pressure.

Again, such a reactance carrying a fault current represents a large amount of magnetic energy stored up, to be suddenly returned to the system as electrical energy directly the circuit is opened and constituting, in itself, a fruitful source of over-pressures. The use of a reactance, therefore, is only permissible when combined with sufficient ohmic resistance to limit the earth current to a small value, that is to say, on systems working with a more or less "floating" neutral. In a modern station running with an earthed neutral the use of a reactance cannot be regarded as a practical proposition.

* *Journal I.E.E.*, 1914, vol. 52, p. 1.

Magnitude of the Current to be Passed.

With pure overload tripping the current passed on the occurrence of a dead earth must clearly be greater than the current-setting of the largest circuit breaker on any feeder. On small and medium-sized systems this may be satisfactory and the earthing resistance, if of the Brazil negative-coefficient type, can be so proportioned as to pass slightly more than this current at the end of 15 or 20 seconds. The current passed during the first few seconds will be perhaps 60 per cent of this amount, and might be enough to clear a fault at any outlying point after an interval depending merely upon the time setting of the relay in question. If, on the other hand, the fault is on the largest feeder it may take 10 or 15 seconds to clear, unless the resistance is such as to pass an initial current in excess of the tripping current of the breaker in question. For this reason it is well to provide leakage or differential tripping, at any rate on the larger breakers, so as to ensure the rapid isolation of the fault, and if this is done throughout it will, in most cases, allow of a considerable reduction in the capacity of the earthing resistance.

Whilst it is impossible to lay down any hard and fast rules as regards the current-settings of the relays or the best value for the earthing resistance, since each case must be considered upon its merits, the table on page 405 may serve as a guide.

In calculating the setting on the basis of column 2, allowance must be made for the distribution of the fault current between parallel feeders, should such exist.

In applying the third column it will often be found that the generator protection entails a larger current than that of the feeders. With differential overload generator protection the current-setting cannot be reduced to a very small value for fear that a want of balance should cause it to operate with a heavy forward current. In this connection the author would suggest that the relays might advantageously be given a percentage bias control, on the lines of the relay illustrated in

Fig. 10, since the comparatively heavy current required for the operation of the generator relays is often a disadvantage, neutralizing to a large extent the benefits of leakage protection for the feeders. With reverse relay protection, this objection does not apply to the same extent since the operation depends upon the direction and not upon the magnitude of the current. In the case of parallel feeder protection the figures given in the last two columns must be multiplied by 2 for two feeders in parallel and by 1·5 for three such feeders.

When "straight-through" current transformers are used, as should be the case wherever possible, the value of the current passed by the earthing resistance should not be less than 100 amperes. With an earthing resistance having a negative temperature coefficient the figures given in the last column may be taken as being the initial current. If the resistance has a large positive temperature coefficient they must be nearly doubled.

Form of Protection	Current-setting of Relays	Minimum Current in Earthing Resistance
Overload as in Fig. 3	150 % of feeder capacity	150 % of capacity of largest feeder
Overload as in Fig. 17	150 % ,, ,,	150 % ,, ,,
Differential reverse relay as in Figs. 8 or 9 ..	70 % ,, ,,	150 % ,, ,,
Differential reverse relay, biased as in Fig. 10	20 % ,, ,,	150 % ,, ,,
Leakage relay as in Fig. 3	80 % of earthing resistance current	20 % ,, ,,
Leakage relay as in Fig. 17	80 % ,, ,, ,, ,,	40 % ,, ,,
Merz-Price or Merz-Beard generator protection	40 % of generator capacity	50 % of capacity of largest generator
Reverse relay generator protection	25 % ,, ,,	35 % ,, ,,

Methods of Tripping.

The necessary current for operating the trip coils of the circuit breakers may be derived from any of the following sources :—

(1) Alternating current supplied by a potential transformer.
(2) Alternating current derived from a current transformer in the circuit affected.
(3) Direct current from a battery or dynamo.
(4) Direct current from an a.c.—d.c. machine upon a principle suggested by Mr. F. Ayton.

The first method is to be deprecated unless an entirely independent source of alternating current is available, since the pressure is likely to fail just when most urgently required.

The application of method 2 is shown in Fig. 25. The contacts of the relay (R) are normally closed so that the circuit breaker trip coil (T C) is short-circuited. When the relay operates, the contacts open and the current from the current transformer (C T) passes through T C and opens the circuit breaker. Although, at first sight, this would appear to be an effective method of tripping, it is, in point of fact, far from satisfactory. The relay contacts have to carry a comparatively heavy current at low voltage, involving mercury cups with their attendant evils. The available current varies from that due to a small overload up to a dead short-circuit, so that the secondary power available for tripping is uncertain in value and is at times considerably more than can be satisfactorily dealt with by the relay contacts inside the case. With leakage tripping, moreover, the current supplied by the current transformers may be insufficient satisfactorily to operate the breakers. All things considered, therefore, this method should only be adopted when no other is possible.

When method 3 (direct current) is available, it is by far the best, an accumulator battery being the ideal arrangement. The current derived from an exciter is occasionally used but is not to be recommended since, on the occurrence of a severe fault, the exciters are apt to become unstable and cases are on record where extremely high voltages have been induced in the exciter circuits owing to a single-phase short-circuit in the generator.

For substations and other situations where there is no available source of direct current, Mr. F. Ayton, some years ago, suggested to the author a system which might perhaps be called "momentum tripping." The method consists in driving a small direct-current generator from an alternating-current motor, the generator serving as a source of energy for actuating the circuit breakers. In order that there might be no possible lack of direct current, even in the event of a failure of the alternating-current supply—quite a likely contingency—the set was to be provided with a very heavy flywheel. Calculation shows that the weight of the flywheel required to give an ample reserve of power is by no means excessive. At the same time, ingenious as this proposal is, a storage battery undoubtedly

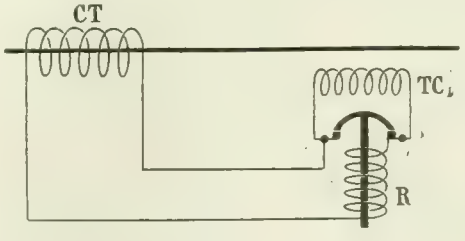

Fig. 25.—Circuit-breaker trip coil operated from current transformer.

forms the best "flywheel" and is easily charged, either through a rectifier or by means of a small a.c.—d.c. set. The latter requires little attention and can, if necessary, be left running, entirely unattended, across the terminals of the battery, much as is done in the case of the charging dynamo on a motor car. Provision should of course be made for giving the battery an occasional discharge.

The Checking of Relay Settings.

If accurate time and current settings are to be obtained, it is essential that the current transformer should have the required ratio curve over the working range, and it is advisable for relays and current transformers to be tested in combination. It is well known that the magnetizing current of a current transformer increases under short-circuit conditions to such an extent as completely to throw out the ratio curve. Fortunately the ill-effects upon an overload relay are not, as a rule, serious owing to the fact that the time-lags are almost independent of the current above, say, 4 times the current-setting (see Fig. 6). In the case of differential and leakage tripping the actual ratio is of less importance than exact similarity of ratio curves. At the same time,

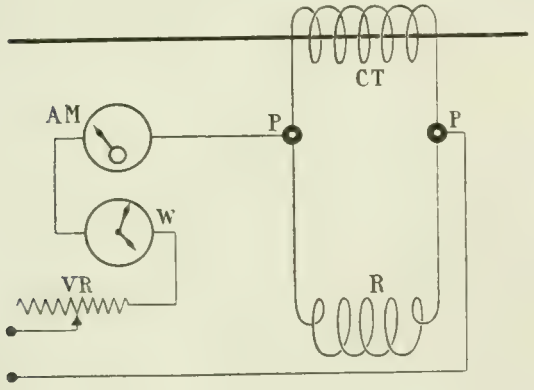

Fig. 26.—Connections for the combined testing of current transformer and relay.

it is well to test current transformers and relays as a single unit wherever this can be done.

A method recommended by the Protective Devices Committee of the American Institute of Electrical Engineers, is shown in Fig. 26. C T represents the current transformer and R the relay coil. The testing current is applied through a variable resistance (V R) to the terminals of the current transformer (which is, of course, dead) at the points P P, which may conveniently take the form of testing sockets. It will be seen that the current flowing through the ammeter (A M) is the resultant of that through the relay and the exciting current of the transformer. But the resultant of these two quantities (multiplied by the ratio of the transformer) is equal to the corresponding primary current. Thus it is easy to calculate what current to pass through A M in order to reproduce in the relay (R) the current which would flow through it under working conditions for any given current in the primary.

The current is adjustable by means of the variable resistance (V R), and the stop watch W is, preferably, so arranged as to be started by the closing of the testing circuit and stopped again by the operation of the relay, so that the interval between these two events can be accurately measured. This method not only deals with the time and current settings of the relay but also tests the secondary wiring for short-circuits and continuity and the current transformer for a short-circuit or an earth. After testing a current transformer at a heavy overload in this way, care must be taken to demagnetize it thoroughly by gradually reducing the current to zero.

Protection of Current Transformers Against Over-pressures.

This is a matter of considerable importance since, whilst reasonable accuracy is required, freedom from breakdown is absolutely essential. Unfortunately the current transformer feeding a relay is, from its position

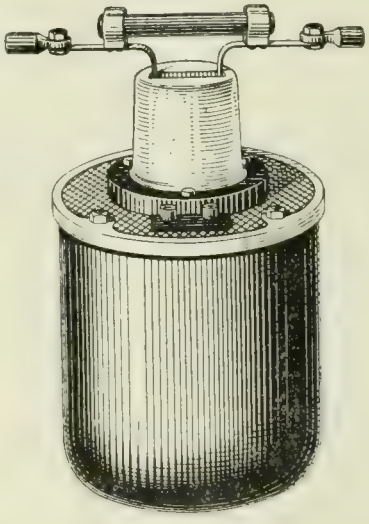

Fig. 27.—Current transformer protected against over-pressures.

at the end of a line, particularly exposed to damage by surges and steep-fronted waves; in fact, except possibly for a line choking coil, the current transformer is the first reactance which such a wave meets as it rushes in from a feeder. In order to avoid a breakdown between turns, the use of straight-through current transformers is to be recommended wherever possible, but on the score of accuracy this cannot well be done if the setting of the relay operated by it is less than 100 amperes. Incidentally, it may be pointed out that this forms an added reason why measuring instruments should not be fed from the same current transformers as the relays, since the former have to be accurate from the lower limit of their range upwards, whereas, with the latter, accuracy of ratio is usually immaterial below, say, half load.

Where multi-turn current transformers have to be employed on lines liable to surges—and few can be considered immune—it is advisable to bridge the primary winding by a non-inductive resistance which

forms a by-pass for the surge and thereby relieves the strain between the turns of the winding. Fig. 27 shows such a resistance as applied to a tank-type current transformer. So long as the value of the resistance is adapted to the impedance of the current transformer the accuracy of the latter is not appreciably affected.

Conclusions.

The points which the author has endeavoured to make may be summed up as follows :—

(1) In any scheme of protection, continuity of supply should be the first consideration, simplicity the second, and adaptability the third.

(2) The neutral points of generators and step-up or step-down transformers should be earthed through a resistance having a negative temperature coefficient.

(3) When the neutral point is not available the system can be earthed through a zig-zag transformer and an earthing resistance.

(4) In a large number of cases special conductors are out of the question, but any and every part of a distribution system can be protected by overload, reverse or leakage relays in accordance with one or other of three alternative methods as follows :—

(*a*) For independent single feeders: combined overload and leakage protection with graded inverse time-lags (Fig. 3).

(*b*) For independent parallel feeders: differential reverse relays with short inverse time-lags (Figs. 8 or 9).

(*c*) A single interconnector between two generating stations can be treated as an independent feeder and protected at each end as in (*a*) above.

(*d*) For a ring main consisting of single feeders: combined overload and leakage reverse relays with graded inverse time-lags (Fig. 17).

(*e*) For interconnectors or ring mains composed of parallel feeders: differential reverse relays with short time-lags (Figs. 8 or 9).

(*f*) Any of the above arrangements can be supplemented by minimum voltage protection at the substations where this seems advisable.

(*g*) For the protection of generators running in parallel, voltage-compensated reverse relays with short time-lags are effective against all faults, and may be relied upon not to act prematurely.

(5) All overload relays must have similar time/current curves, with a definite minimum, independent of the overload.

(6) All reverse relays must be compensated for a fall of voltage down to 2 or 3 per cent and may in some cases be required to operate with a heavy current in either direction at zero voltage.

(7) Current transformers should be of the straight-through type whenever possible, and should otherwise be protected by a non-inductive shunt of ample current-carrying capacity and specially adjusted to the transformer characteristics.

Discussion before The Institution, 12 February, 1920.

Mr. E. B. Wedmore: The author has collected a useful group of protective devices in the compass of a short paper, and has also described several devices which are new—new in the sense that they have not previously been described or discussed. I should like to deal with one or two of them. Fig. 10 shows a bias arrangement of reverse-current relays which has distinct utility. It is not very fully described in the paper, and I will add one or two comments on it. It will be understood that the two current transformers shown will not balance, and in fact cannot be made to balance absolutely under all conditions. Under severe conditions there will be an appreciable current circulating between them and therefore through the relays. That current may be in either direction according to which transformer predominates at the moment, and therefore one or other of the relays will tend to operate. Now to overcome this the author has added restraining coils which exert a force proportional to the current in the feeders. This need be but a relatively small force in order to wipe out quite readily the effect of any unbalanced currents that may flow. But the force, being proportional to the currents in the feeders, will be small when there are only small currents to be dealt with, so that the relay remains a sensitive device. Sensitiveness is not sacrificed, while at the same time troubles due to small inherent unbalancing of the transformers are entirely disposed of. That is the essence of what has been described hitherto as the bias principle, and this is a very good example of its application. In Figs. 15 and 16 the author advocates a novel solution of the problem of the protection of interconnectors and ring mains, by the use of an arrangement of reverse current relays. I am not satisfied that the device will do all that will be required of it. The author shows how fault currents, according to their position in the system, will circulate either clockwise or counter-clockwise, so that if a relay is put in at a certain point operating on the clockwise current it will not operate when the fault is on the other side of the relay. Currents will flow, however, in these same directions when there are faults in the apparatus at substations or in the feeders connected to the substations, so these relays will be subjected to currents which will operate them when faults occur outside the ring. Discrimination could be obtained only by adding a time-limit device to the relay, but I do not think this solution will oust the Merz-Price, split-conductor, and similar solutions which have been offered, and which provide a complete solution of the problem of dealing with interconnectors. Turning now to Fig. 17, we have a novel leakage relay, shown here in combination with overload relays. This leakage relay has the feature that it can be inserted at any point in the system, and will show on which side of that point the fault is. It is a suggestion of my own, and is, I believe, the only known solution of the problem of making a completely discriminating leakage relay. It has not been published

previously for the reason that its use involves earthing the middle point of the potential transformer, and hitherto there has been a great deal of prejudice against doing so, but engineers now have a better understanding of what is involved, and the device may come into its own. The fourth novel device is illustrated in Fig. 13 and is, I think, worthy of further consideration. Designers of reverse relays in the past have generally offered either a relay which they claimed would open the circuit in any case under very severe conditions, or else a relay which under very severe conditions would at any rate not open incorrectly. That has been as far as most designers have got; in other words, either they gave up the attempt to produce a proper discriminating relay or the relay itself failed when the conditions were severe. I believe we now have the explanation of that, although it is one which has eluded designers hitherto, and even the author has not succeeded in giving it. I will endeavour to do so in a few words. Consider for a moment the action of a wattmeter; all reverse relays are imperfect wattmeters. If the power factor is unity and the current flows in the forward direction the wattmeter will rotate in one direction. If the current lags behind or leads the voltage by any angle up to practically 90°, the wattmeter will rotate in this same direction, so that within a range of 180° the wattmeter will rotate in one direction. For the opposite range of 180°, however, the wattmeter will rotate in the opposite direction. The designer utilizes this feature by preventing rotation in one direction and utilizing rotation in the opposite direction to actuate the relay contacts. The author's diagrams show, however, that on a three-phase system under short-circuit conditions, quite apart from any change of the power factor in the faulty circuit, there is an additional change of 90° in the relation of current and potential, which change may be in either direction according to the phase in which the fault occurs. That swing of $\pm 90°$ wipes out the whole safe limit of 180° which the relay should have had, and leaves us with a relay the movement of which is quite indeterminate. This is, I believe, the real explanation why reverse relays, which on paper prove so promising, have in practice frequently come out when they should not have done so, or stayed in when they should have operated. That difficulty is got over by the device which the author has partly described, of taking the potential connection to the relay off the side of the delta opposite to the phase from which the current is taken. To convert the relay back to a wattmeter one must then use a condenser or equivalent device. As a matter of fact, one does not make the relay a perfect wattmeter. It is given its maximum sensitiveness with a reverse current with a lag of, say, 45°, and then over the whole range of lagging currents the relay is very nearly equally sensitive; and the swing of 30° in either direction, which the author describes as taking place, still keeps a long way outside the danger zone. It should be noted that this swing of 30° can occur only provided the fault is not heavy enough to pull down the voltage, so that in practice the relay has a useful characteristic with a range approaching 180°, and will be safe for use with generators or on feeder circuits. The relay was got out for a large existing installation where it was impracticable to use Merz-Price or split-conductor apparatus, and it has given excellent service. I recall one case in which, on one pair of 20,000-volt lines, 19 severe faults occurred during a period of three months, and the relay discriminated correctly every time. I am not going to say that the supply was maintained to every customer every time, because that was not so. The use of a correctly discriminating relay brought out the fact that there were certain conditions of service on overhead lines which cannot be met by any discriminating device. If there is a disturbance on one line an adjacent line is very likely to be disturbed just about the same time by the same conditions of the atmosphere, and with reliable discriminating apparatus one is able to follow what occurs. One line goes out, and within a few minutes the other line goes out by a continuation of the same disturbance. Experience with split-conductor and other protective systems has borne this out, and it is found advisable with overhead lines, if we want to maintain supply, to keep the parallel feeders at least a quarter of a mile apart and bring them in by opposite routes.

Mr. J. R. Cowie: It is with some diffidence that I begin to criticize the author's paper because, as he points out, every system has to be considered upon its merits, and at some point or points a selection of almost all the known methods of protection must be employed. This protection becomes more complicated and final decisions more difficult the greater the cable density in any given area, and is governed not only by high-tension characteristics but also by machine characteristics, especially where interlinking of the low-tension networks takes place. If we refer to Fig. 3 we find there a well-known example of simple protection. On the Glasgow system this is employed on every converting machine and upon every single transformer. When, however, I come to banks of transformers discriminative apparatus is used, and on generators overload and discriminative gear. The operation time for this overload material is in round figures 1 second for a complete clearing of a fault. We set it as low as possible, but the time given ought to be divided by five to minimize shock. The apparatus shown in Fig. 3, with the addition of a no-volt release, is what I should like to see standardized for machine protection in factories. The leakage coil can be fitted with a time-lag, or be full-load leakage or any percentage thereof which charging current conditions will allow; and to make such apparatus reliable under transitory overload conditions more attention should be paid to series transformer characteristics and their balancing with one another. When, however, I come to feeder protection, discriminative gear is used, and whilst provision is made to fit overload apparatus if necessary, overload protection is only used as a last line of defence, that is at the power station or at vital section points. In this case leakage is omitted, three overloads are used, and the time setting is, as stated above, approximately 1 second. As regards the relay times given on page 393, to ask for a time setting of $1\frac{1}{4}$ to $1\frac{1}{2}$ seconds is futile. On a mixed plant with the time stated in the paper the rotating machines will be out of step, and if

the shut-down is not on the alternating-current side it will be on the direct-current side if interconnecting of the network takes place. I was interested in the value of one-fifth to one-quarter of a second mentioned below Fig. 5, because on a selective protection device system we are trying to get the faulty apparatus clear in under one-fifth of a second. Switchgear can be bought to do so, and also protective gear. Tests which I have made, show that on consumers' gear the fault is cleared between the fourth and fifth periods, and on the heavier distribution gear about the fourth period, the periodicity of the supply being 25 cycles. Fig. 5 advances the American argument that all switches must be delayed so as to avoid the peak wave. True, if it can be done, but nothing has yet been devised to avoid the recurring short-circuit. I have stood alongside a joint which failed and which gave no less than five recurring short-circuits before the switch cleared. The cable was provided with overload inverse time-limit protection. Such conditions will some day occur on any system; then the switch, which is in all probability already on the move, will be expected to open the circuit at the peak of the wave and it has got to do so or there will be a disaster in the switchroom. When one has said all this one must be fair to the author. There may be positions on an old network where no other gear than overload protection is possible, and all I can say is, I am sorry for the man who has to work out the discrimination. The author claims that it can be done. So far we have not been able to do it satisfactorily. With regard to the type of relay setting to be used, I agree that the inverse time limit is preferable for ordinary working, but I must confess to a regard for the solenoid type of relay owing to its simplicity and the small number of moving parts. Many people, however, prefer wherever possible to use direct-connected relays and so do without contacts and tripping batteries. With regard to the author's remarks on page 394, I have both Merz-Price and split-conductor selective apparatus. The former fails in that straight-through faults can operate the gear. This can be got over to some extent by using distributed air-gap transformers and compensated cables, or by using bias coils. There is something attractive in the use of bias coils as a delaying agent, but when bias coils are used there is generally something fundamentally wrong somewhere else. If the pilot cables go wrong, Merz-Price protection is out of commission. Split-conductor protection is very sensitive and requires, it is true, a special six-core cable and switches. The cable has, however, compensations in increased loading, and the switches, if well designed, present no operation difficulties. I have yet to find this material operate on a straight-through fault, except when two three-core cables are used in parallel and these are not truly balanced. I understand, however, that switch difficulties are likely to arise if this material is ever used on very high pressures, say 100,000 volts. The method shown in Fig. 8 is principally of use when the two feeders are of unequal length or unequal size and the current-transformer ratios are chosen to suit the load division. It fails because it calls for potential transformers, than which no more dangerous apparatus can be used on any system. If the feeders are within reasonably equal lengths I would prefer to put them into one split-conductor switch, thus saving space and reducing the material requiring attention. Can the author say what time the relay will take to operate with such connections at full secondary current? The statement on page 396 is perfectly correct, but the clause at the top of page 394 re overloads, when one reads page 396 and then refers to Fig. 17, shows inconsistency in argument. We have again to be fair to the author. There are on every system places where the reverse relays will be an advantage, but it is quite evident that on any system the last line of defence is the overload relay. These items should, however, be a minimum. Every page of the paper contains items worth discussion, and I could give conditions where extensions would put out of gear some of the conclusions arrived at on the typical network diagrams. We arrive then at this conclusion, that what on one system is good practice is on another totally wrong, and such a condition resolves itself into a court of inquiry upon every failure. Consultations between the chief operating engineers and the technical advisers are imperative, and close co-operation between these parties is essential. Only so, and by improving the gear after every failure, can success be attained, and in no case is finality ever reached. The author calls for special series transformers for his relays, and so do other protective schemes; the metering expert calls for special series transformers for his meters, and the instrument man wants transformers for his apparatus. I therefore conclude these remarks with a few "Don'ts." (1) Don't use any more series transformers than absolutely necessary. Reduce to a minimum the number of instruments these transformers have to drive, so that the series transformers may have straight bar primaries or be as near to this ideal as possible. Panels full of instruments are beautiful, but most of the information we desire can be quickly calculated. Power-factor indicators, for instance, are only useful on booster-type rotary converters, or on synchronous machinery, or for a special purpose. (2) Don't use potential transformers unless absolutely necessary. (3) Don't meter on the high-tension side if the low-tension side is available. Finally, get down to absolute simplicity in the material used. The protective gear at Dalmarnock station is as follows:—

Switch capacity: 1,500,000 k.v.a., and this clears the fault at the sixth period when split-conductor gear operates.

Generator protection: Circulating current with series overload fuses, and light time-limit fuses in parallel with the relay.

Coupler and reactances: Overload with definite time limit.

Feeders: Split-conductor and overload with definite time limit.

Works transformers: Merz balance with series overload fuses, and light time-limit fuses in parallel with the relay.

Mr. A. M. Taylor: The relay shown in Fig. 11 has a very excellent feature in the low voltage at which

it will operate. If, however, it were to be used near to the source of current, it might have to operate under short-circuit conditions, when, due to a fault near the station, it might have to work under as low a power factor as 0·25. Will the author please state what the operating currents would be for power factors down to this figure and with the lowest voltages. Will he also please state at what "forward" current and voltage the relay operates, and whether the results in Fig. 12 were taken with a relay having this characteristic. With regard to the question of breaking large currents, and particularly the author's Fig. 5, I have recently been applying the equations established by Steinmetz (in his book on "Transient Phenomena") both to the case of interrupting the full-load current of the station and to that of interrupting the short-circuit current. I have introduced into these equations constants more in conformity with the conditions obtaining in this country than are those assessed by Steinmetz, and I am rather alarmed at the result. The equations show that under bad conditions of feeder arrangements it is possible, even where we break the circuit when the current passes through zero, to get voltage oscillations up to double or treble the normal voltage; while if we break it when the current is at its maximum, we may get anything up to 10 times the normal voltage. Now it is trading too much on good luck to assume that such a condition, or even a partial move towards it, will never occur, and therefore it appears to me that two points should urgently be striven for, namely (1) To have as many trunk feeders as possible in parallel as we approach the main station, each absolutely independent of the other (split-conductor protection preferred), so that any feeder may momentarily be thrown out without the main generator circuit being broken; and (2) to use core-balance or the most delicate protection obtainable, in order to cut out every feeder before the leak to earth has time to develop into even a mild short-circuit between phases. I would recommend this course even at the expense of such tripping being, in some few cases, afterwards found unnecessary. This would be allowable when several feeders were in parallel, as I have recommended should be arranged. I regret that I find myself quite at issue with the author on the question of time-lags. The intervals given are altogether too short. I should like to ask him how he would protect, with differential reverse relays, a group of six feeders in parallel, some of which were 80 per cent longer than others, and some of which were fed through reactances while some were connected direct to the busbars. With reference to the remarks on page 396, to the effect that combined leakage and overload protection should be applied to the outgoing feeders, has the author considered that, unless very coarsely set, the leakage relays will bring out both the sound and the unsound feeders? I fully agree with the author's recommendation that the short-circuit currents should be worked out for all important points of the system. Speaking generally, combined overload and leakage protection are all right for the outskirts of a large system and for dealing with existing mains, in the absence of anything better; but they are not, in my opinion, suitable for the heavier feeders. In support of the possibility of the short-circuit being opened at some time other than when the current is passing through its zero value, I should ask the author to consider that the oscillating electromotive force is at its maximum when the current wave is approaching or leaving zero. The insulation might therefore break down just at that moment, followed of course by an immediate rush of current, which the forward motion of the breaker must interrupt, at once giving the most dangerous conditions.

Mr. G. W. Partridge : Whilst we are on the subject of the time-lag of relays and disconnecting circuits at the top of the wave, I think it might be of interest if I described my experience in those particular cases. I entirely agree with the author's statement on page 393 that "more interruptions of supply are caused by opening circuits prematurely than by leaving a fault on the system for too long a time." The Merz-Price protective device generally opens the circuit before the fault has turned into a short-circuit between phases. But if a short-circuit between phases takes place, the later the switch acts, provided it works quickly when it does act, the better. Two or three years ago we unintentionally connected capacity in the shape of a length of cable across the terminals of an oil switch. As a consequence, when we opened the circuit with a load of about 400 or 500 kw., the oil switch was trying to snap the arc out instantaneously or at the top of the wave, and as a consequence we burnt up the entire switch. As I thought the reason of the failure was want of oil in the switch we installed a new switch, repeated the experiment, and burnt up the second switch. We then tried the experiment over again at a lower pressure with an oscillograph and found that on a 2,500-volt circuit the pressure at the time of rupture went up to about 20,000 volts. It will generally be found that if direct-current circuits are broken by means of oil switches one will have a similar experience. To my mind it is quite impossible to break these short-circuits on alternating-current systems with oil switches, except at the zero line. The author and people like Mr. Wedmore will design a relay to do practically anything, but I, for one, think that the simpler and the fewer these relays are, the better. The author refers on page 407 to tests on relays. It is most important that all these relays should be tested not only in the shop but, if possible, with the whole of the apparatus to which they are connected in actual use; otherwise, when a short-circuit does occur—possibly after several years—the relays on which one has been depending may not act. I know of a generating station not far from here where I was shown a switchboard on which I should think 75 per cent of the relays were wedged up and tied with pieces of wire so that they could not act, because when a short-circuit occurred every switch opened. I think there is a great future for single conductors for underground single-phase and three-phase systems, more particularly on the lower periodicity. I know there is a good deal to be said against it, but at the same time I think single conductors will probably be used underground when working at the pressures which are now being talked of—between 30,000 and 60,000 volts—and such protection as is shown by the

author will of course be most useful. I should like to say a word in conclusion with regard to the Brazil resistances. I have had in use for many years one suitable for 200 amperes and it has worked most satisfactorily. At one place in the paper the author seems to infer that some of these relays will not work with a drop in voltage. There is a well-known system of protection which has been thought out—and I believe it is in use—in which the generators are provided with special pressure-reducing apparatus, so that if a serious short-circuit takes place, such as the burning up of the generator, these regulators lower the pressure of the system until the fault itself has been removed.

Mr. H. W. Clothier: I cannot find in the paper much really useful advancement which applies to large systems upon what the author published in the *Electrical Review* in 1911. One essential in switchgear construction is always to obtain the simplest protective devices. The devices described in the paper may serve a purpose on small systems and less important connections, but it must be remembered that in time small systems may interlink together and become parts of large power schemes covering extensive areas. Mr. Price when he went to South Africa left leakage protection as a legacy to me, and I have often felt that it has not had its full scope for development. The chief feature of leakage protection is its instantaneous operation in clearing faults to earth. This is particularly desirable for work in mines where there is danger from open sparking. To my disappointment, the author couples with leakage protection the undesirable sluggishness of a time limit, thus depriving leakage protection of its main virtue. We must not allow faults to remain on large power systems; they must be cut out as quickly as possible. If allowed to remain on the system too long they cause (*a*) synchronous plant to fall out of step, (*b*) increased danger of fire, and (*c*) increased damage to plant. Nor is it safe to rely upon time limit to reduce the breaking capacity of switches because of the risk that, during the time interval, the fault may develop and intensify, for instance, from a fault to earth to a more serious fault between phases. In fact it may so happen that the actual instant of separation of the sparking contacts coincides with the maximum current on the short-circuit transient. The author refers to a time-limit fuse as a "capricious piece of apparatus," but in the same paragraph he says that "air dashpots are better." Surely an air dashpot is less reliable than a fuse. The author says that "definite" time-limit devices are innocuous, and he prefers the use of "inverse" time-limit devices. Fig. 6 shows, however, that in practice the "inverse" time-element feature only appears in the first 50 per cent of overload. Faults as a rule are not of 50 per cent overload but rather of 10, 20 or more times the normal load current, so that the "inverse" time-limit relay really becomes a "definite" time-limit device, and a bad one at that on account of its low range of time-setting. If the protection of a system is to depend upon the discriminating effect of time-limit devices it would seem better to use relays with "definite" time-settings than those which lose their discriminating powers when certain limits of overload currents have been passed. There are a number of other points to be discussed. The arrangement in Fig. 27 is a complication and quite unnecessary. It is better to make a good job of the insulation between the primary turns than to resort to such contrivances.

Mr. H. Brazil: I have always thought that the maintenance of the continuity of supply is the chief thing to aim at in a supply system, and I am pleased to see that the author gives this the first place in his paper. This paper emphasizes the importance not only of putting in protective apparatus, but of installing it in the right place. I am afraid that in many undertakings in this country protective apparatus, excellent in itself but unsuited to the particular undertaking, has been installed at the wrong points. This is particularly the case with undertakings which have been in existence for some considerable time and which have been extended. In some cases within my experience circuit breakers with no time-lag were installed at the generating station, and automatics with time-lag at the substations, with the result that a fault on a motor-generator would cause the circuit breaker at the generating station to come out before that at the substation. With regard to the different types of relay, I have experimented with the induction type described by the author, and find it to be a very reliable piece of apparatus and preferable to either the fuse-shunted solenoid, or to the dashpot type. The importance of using a relay having an inverse time-lag cannot be overemphasized, and although when a dead short-circuit occurs the time before the relay acts is short, it is generally long enough to prevent the breaker coming out on the maximum short-circuit current. The current flowing when a fault comes on can only be excessive when there is a short-circuit between phases, as the earthing resistance, which is now nearly always installed in the neutral point, limits the current to earth to a predetermined figure. I am in agreement with the author when he states that more interruptions of supply are caused by opening a circuit prematurely, than by leaving a fault on the system for too long a time. I am therefore in favour of installing a resistance which allows the minimum current to pass at the moment when a fault occurs, always provided that if the fault is not cleared the resistance will eventually allow the current to increase to the figure necessary to trip the circuit breaker. The iron-grid resistance does not comply with these requirements, as it increases in ohmic value as it heats up, and therefore reduces the current. I think, however, the author has put the increase of the ohmic resistance in an iron grid a little too high, as I have found by experiment from cold to red heat the increase is about 33 per cent. With regard to earthing through a reactance, I wish to endorse strongly the author's opinion that this is the wrong practice. I have had some experience of surges and resonance, and I think that one is inviting trouble by putting an inductive coil between the neutral point and earth. Sooner or later the particular proportion between inductance and capacity favourable to resonance will be reached, and then the reactance coil would be more a source of danger than of safety to the system.

Dr. R. D. Gifford: Reviewing the paper as a whole, it appears that one of the objects is to discuss the uses

and the merits of the carbon-powder resistance with the negative temperature coefficient, and also of the reverse relay compensated for voltage variation. In the second column on page 395 there appears to be a certain looseness of diction where the author says; "This condition necessitates the installation of a larger earthing resistance than would otherwise be necesssary." He obviously means a resistance of lower ohmic value. With regard to the reverse-current relay shown in Fig 11, it would be of interest if the author would state how he manages to get the torque in the case of very heavy forward currents at no voltage. I do not quite see where the torque comes from unless it is from an eddy-current effect of some kind. The author also says in connection with Fig. 11 that if we have two parallel feeders, after one has been cut out the other is left without protection, and he advocates the installation of an overload relay. When both feeders are sound and are carrying anything like full load, if one develops a fault and is cut out the other one will necessarily have to carry about twice full load, and with the overload protection which the author provides it would seem that that might very possibly operate on a peak, in which case even the sound feeder would also be cut out. The next point I want to take up is on page 397, in which the author refers to two feeders in parallel of different cross-sections. He there points out that he would put in transformers having appropriate ratios. I presume that that is only a first approximation, as the current taken by two such feeders will not necessarily be in proportion to the sections of the feeders. If they are long feeders the capacity and self-induction will play quite a large part in regard to the way in which the current will be split between them. Moreover, with two feeders having vastly different cross-sections, as might easily occur in practice, they would have heating and cooling characteristics of quite a different nature, in which case when they were cold one might get a balance, but after they had been on load for a considerable time the balance might be sufficiently upset to trip a delicate piece of apparatus. I should like to know whether the author has found any difficulty in that way and whether the effect of the capacity and self-induction is provided for by using transformers having tappings on the secondaries, so that the ratio can be slightly modified as experience dictates. In connection with the single connector shown in Fig. 14, the author appears to be satisfied with overload protection only and makes no attempt to provide against incipient faults, as does the Merz-Price system. This is a disadvantage, as the proverbial "stitch in time" applies with peculiar force to expensive cables. In connection also with the protection of the generator the author rightly points out that, in the case of the oil switch tripping as a consequence of a leakage or something of that nature, it is necessary to cut out the field at once, but he says: "The circuits must, moreover, be so arranged that if the main breaker is tripped by hand the field is not opened." I am not quite clear why that should be so. It seems to me that in every case when the generator is taken off the line, its excitation should also be broken.

Mr. H. Pearce: It is very much easier to design a suitable protective system if one has a free hand as to the nature of the conductors and other details; but where one is confined to simple conductors it is a much more difficult problem. In Fig. 12 the reverse relay appears to be quite satisfactory so long as the operating voltage is not less than 2 per cent of the normal, but I think this is by no means low enough. If one considers a feeder which has a 4 per cent impedance drop, and assume that a fault develops so that the current rises to 20 times the normal, that means that the drop over the whole length of the feeder is approximately 80 per cent of the normal voltage. Now, the fault may be only a short distance from the substation bars, and the voltage available to operate the substation relay is under the worst conditions only the drop between the substation bars and the fault, so that if the fault is in the cable box in the substation the voltage across the relay has practically gone altogether. That is a most serious difficulty in the use of reverse relays, and I think it is the real reason why they have never been used successfully in this country. I say "in this country" because in America they have had in use for some years a much more delicate relay than is referred to in the paper. Instead of operating at a limit of

FIG. A.

approximately 2 per cent of normal voltage it goes down to something like one-tenth of 1 per cent. That means that the relay is liable to operate on a surge where the power may blow backwards and forwards. The Americans get over that trouble in this way. They have a second relay element operated by current only, and they connect the contacts of the two relays in series so that the complete reverse relay will not operate unless there is at the same time an excess of current. This represents a marked improvement, but it is generally admitted that it is desirable to make the protective device entirely independent of the line potential wherever it is possible to do so. In Figs. A and B is shown what I believe to be a novel system * of protecting parallel feeders. Fig. A is merely inserted to show that the method is applied to the ends of parallel feeders in the well-known manner, and that no pilot cables are required along the length of the feeders. Fig. B shows the secondary connections only. The primaries of the current transformers A_1, B_1 and C_1 are connected in circuit with feeder No. 1, and similarly A_2, B_2 and C_2 in circuit with feeder No. 2. P_A, P_B and P_C are relays connected in the well-known manner for circulating-current protective gear. The novel feature consists in the insertion of a sensitive relay L R, so that the complete system forms a combination of the circulating current and the core-balance systems. The relays P_A, P_B and P_C may have a relatively

* Patent applied for.

coarse setting, say 100 to 200 per cent of normal—and preferably should be provided with a constant time-lag device adjustable to zero. These three relays take care of phase faults, so that one may be omitted if desired. The relay L R will guard against earth faults. When both feeders are in operation the time-lag device will be set to zero; all the relays will then be instantaneous in action, and it should particularly be noted that they will only operate on faults in the feeders they are protecting; they will not operate on faults on other parts of the system. For example, if an earth occurs in the distribution system, both feeders share the fault current and conductors S_1 and S_2 in Fig. B will carry equal currents, so that the relay LR will not operate. This system gets over one of the old difficulties in this type of protection, viz. the difficulty of getting the feeders into circuit. With the earlier forms, a sensitive setting meant that the oil switches would open on out-of-balance current, as soon as the attendants succeeded in closing them. Provided there is no earth leakage current to operate L R the oil switches can be closed at will, so long as the current does not exceed the coarse setting of the relays P_A, P_B and P_C. Should it be desired to run with a single feeder in

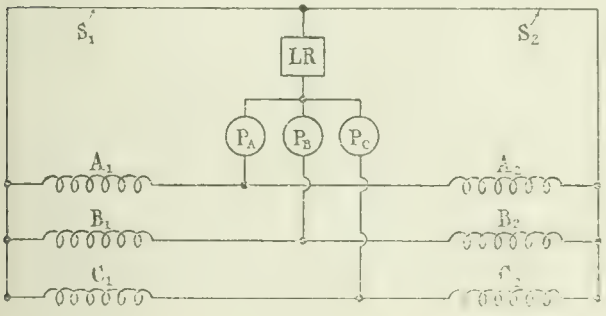

FIG. B.

circuit, the current and time settings of the relays P_A, P_B and P_C may be appropriately modified, and the feeder will then be provided with overload time-limit and plain core-balance leakage protection. The problems of protecting transformers are in some respects similar to parallel feeders, and the connections in Fig. B are quite applicable to the protection of star-star or delta-delta transformers, or generator-transformer combinations. The advantage over the plain circulating-current system lies in the sensitive leakage setting obtained in the relay L R, since relays connected like P_A, P_B and P_C must necessarily have a coarse setting to take care of the rush of magnetizing current on switching on. For transformer protection all four relays should be provided. On page 405 the author gives the setting for Merz-Price and Merz-Beard systems as 50 per cent of the generator capacity. Actually, transformers of the bar primary pattern are used in the Merz-Beard system and the setting is then independent of the size of the machine. The usual setting is from 20 to 50 amperes, primary fault current. The setting for the Merz-Price is also too high. The figure used a few years ago was 50 per cent, but now the standard setting is of the order of 15 per cent. The reason for the change is somewhat interesting. We all know the difficulty of balancing two current transformers, and if a very delicate relay be used, that relay is bound to operate when the transformers carry overload currents. It is like trying to balance two 1-lb. weights against each other on a delicate chemical balance. The solution is to make the balancing medium more robust and that is how the setting has been reduced from 50 per cent to 15 per cent. The relays are provided with a higher impedance, so that the out-of-balance current due to the different characteristics of the current transformers is considerably diminished. The effect is so marked that not only is a lower relay setting obtained, but the safety factor against tripping on overload current is also improved.

Mr. D. T. Powell (*communicated*): In connection with the author's advocacy of a balanced leakage system of feeder protection, it is of interest to recall that the late Mr. E. G. Waters worked out a system on these lines in conjunction with Messrs. Ferranti, in which feeders working in parallel are protected against faults between phases and earth, and I am surprised that the author has made no reference to it in his paper. This system was adopted for the 11,000-volt feeders on the electrified system of the London and South Western Railway. In this case feeders from the power house are taken in pairs to a substation, and have balanced relays requiring no potential coils at the power-house end, but at the substation the relays are of the balanced reverse type with potential as well as current windings. Where feeders are laid in pairs from one substation to another, the relays are again of the balanced type at the supply end, and of the balanced reverse type at the receiving end. After the installation was completed, exhaustive tests were made by switching artificial earth faults on to the feeders at either end, with the result that the faulty feeder was switched out at both ends, leaving the sound feeder on circuit. During these tests the value of the carbon-powder resistance, which was installed between the generator neutral bar and earth, as described by the author, was clearly demonstrated. The fault current was kept down to a reasonable figure which could be determined, and the relays could be set accordingly. Although when trying the relays many times in succession the carbon powder got very much overheated, it suffered no permanent deterioration and proved extremely satisfactory. Fortunately this railway company's system has not, although in regular operation for more than four years, provided much opportunity for proving the utility of these relays in clearing faults occurring under working conditions. It is, I believe, no secret that both feeders between two substations were severed by a bomb during an air raid, but the confused conditions which resulted prevented the taking of any careful record of the operation of the protective system. One defect of this system of protection seems to be that if one feeder fails and is cut out, the second cable of the pair is left without any protection unless it is provided at both ends with an overload relay in addition to the balanced protective relay.

Major K. Edgcumbe (*in reply*): I would preface my reply by quoting from one of the opening paragraphs of the paper itself:—"The present paper is an attempt to show how these ideals can be attained by simple means with well-tried apparatus and without recourse to special conductors which, however desirable in themselves, are, more often than not, quite out of the question." It is for this reason that I have refrained from discussing the relative merits of the various systems of protection involving the use of special conductors, such as the Merz-Price, split conductor, Thompson-Bowden, Beaver, McColl and others —my object being to show what can be done without recourse to such expedients, more especially for the benefit of the very large number of station engineers who find it necessary to overhaul their protective arrangements, owing to the growth of their systems or for any other reason, but who are not blessed with that bottomless purse to which some of their more fortunate brethren appear to have access. Whilst, therefore, I had more especially in mind the requirements of stations of moderate size, it is interesting to find that even on the largest systems, such as those of Glasgow and the North-East Coast, for example, numerous cases arise in which the arrangements I advocate are found to afford the best solution of the problem.

Considerable controversy centred, in the discussion, round the question of the time-lags to be allowed. Some speakers regarded those proposed by me as too long, whilst others, Mr. Taylor in particular, objected that the interval allowed between the operation of successive relays (i.e. $\frac{1}{2}$ second) was too short to permit of a breaker coming out before the one next behind it started to act. To the first of these criticisms I would reply that in the States and on the Continent it has become the regular practice to employ time-lags at least twice as long as those to which I have limited myself; and I would answer the second criticism by referring to a lay-out of considerable size in which five sets of overload relays are connected in series with an interval of only 1/10th second between the "short-circuit" time-lags of each set. This system has been in operation for some years and no case is on record of the wrong relay having acted. I notice that although Mr. Cowie speaks of time-lags of $1\frac{1}{4}$ and $1\frac{1}{2}$ seconds as being "futile," he nevertheless says that at Glasgow "the operation time is in round figures 1 second for the complete clearing of a fault," so that there does not seem to be very much between us in this respect.

With reference to Mr. Wedmore's criticism of the ring-main protection shown in Figs. 15 and 16, on the ground that the current flowing into a fault on the consumers' side of a substation would necessarily pass through the relays in the ring feeders, I would point out that there is no difficulty in preventing the action of the latter on the occurrence of faults on plant connected to the substations, it merely being necessary to see that the protective gear controlling the latter has a slightly shorter time-lag than that given to the relays protecting the ring feeders at that particular point. It must be remembered, moreover, that it is only in the case of single feeders that discrimination by time-lags becomes necessary, since with parallel feeders the arrangements shown in Figs. 8, 9, etc., are available, and these can be made as instantaneous as may be desired.

Mr. Taylor asks about the practicability of applying differential reverse relay protection (Fig. 8) to feeders of varying lengths, some of which are connected through reactances and some direct to the busbars. Unless feeders can be paired it is clearly impossible to apply differential reverse relay protection, but such pairing is usually possible, by means of adjustable reactances, for example. A more serious difficulty arises (as mentioned on page 401) in connection with the protection of parallel feeders from which one or more consumers are tapped off *en route*. Since my paper was read Mr. Wedmore has drawn my attention to the advantages of the method of differential leakage protection outlined by him in his 1914 paper* for this purpose. It is shown, in elementary form, in Fig. C herewith, which represents the outgoing end

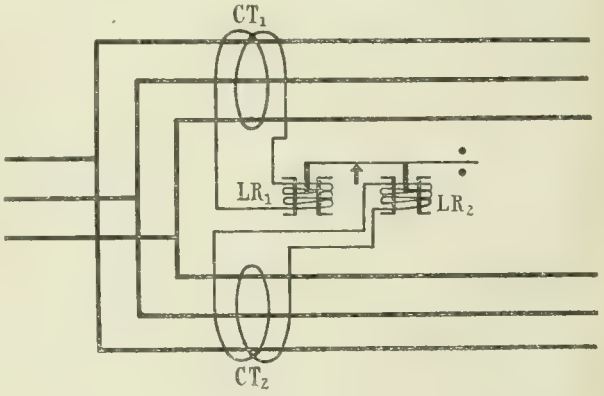

FIG. C.

of two parallel feeders. C T_1 and C T_2 are current transformers, each consisting of an iron core surrounding all three phases of one feeder. The secondaries of these transformers are connected to the coils L R_1 and L R_2, respectively, which therefore carry currents proportional to the leakage current if any. Should a fault occur on the upper feeder the leakage current in LR_1 will be greater than that through LR_2 and the beam will tilt, thereby causing the breaker on the upper feeder to open, and vice versa. It will be seen that this arrangement allows of consumers being tapped off either feeder, at any point, and protects not only the feeder but also the high-tension side of such a consumer's transformer. At the substation end of the feeders, differential reverse relay protection, as in Fig. 8 of the paper, should be used in the case of independent parallel feeders, thereby ensuring isolation of the faulty one at the remote end, even should the fault occur near the substation. This arrangement is not applicable to interconnectors or to ring-main feeders, and in such cases it is certainly better practice to avoid taps, as far as possible. The arrangement shown in Fig. C corresponds to that of

* *Journal I.E.E.*, 1915, vol. 53, p. 152.

Fig. 2 in the paper and affords protection against earth faults only. It is, however, easily extended to embody overload protection as well, on the lines of Fig. 3 in the paper, the coils $L R_1$ and $L R_2$ of Fig. C taking the place of the leakage relays, such as $L R_1$ in Fig. 3.

Speaking of the protection of consumers' installations, I am pleased to hear from Mr. Cowie that in Glasgow they are protected on the lines of Fig. 3 in the paper, since faults on the consumer's premises are such a frequent source of trouble on the network. I can fully endorse his recommendation that a similar arrangement, with the addition of a no-volt release, should be used for machine protection in factories.

Mr. Partridge's suggestion of lowering the generator voltage on the occurrence of a fault is interesting, but it seems doubtful whether the action could be rapid enough to be of great value; also, is it not a little like burning down one's own house to prevent someone else from setting fire to it?

I cannot agree with Mr. Clothier when he says that in his opinion the chief feature of leakage protection should be its rapidity of action. To my mind the outstanding feature of leakage protection is that it limits the fault current to a definite and predetermined value, compared with the altogether indefinite current which flows into a short-circuit, and, moreover, the leakage current is usually such a moderate one that it can be left on the system for a considerable time without in itself doing any damage. The consideration which, in practice, limits this time is that the feeder must, of course, be isolated before the earth fault has developed into a short-circuit between phases. *Other things being equal*, therefore, the shorter the time-lag the better. No one would think of unnecessarily prolonging it, and for that reason I have suggested an upper limit of 2 seconds, although, at the same time, pointing out on page 393 that a delay approaching one second has distinct advantages for other reasons, even in the event of a short-circuit between phases. I would again repeat that time-lags of any length become quite unnecessary under the systems I have advocated, except for the protection of large systems involving single feeders only, which are, of course, rare. I entirely agree with Mr. Clothier when he says "it would seem better to use relays with definite time settings than those which lose their discriminating powers when certain limits of overload currents have been passed," but since relays are available which, as shown in Fig. 6, will not only retain their discriminating power at all overloads, but will also allow an increased time-lag at small overloads, I suggest that for most purposes it is preferable to employ them.

I cannot quite follow the numerical example given by Mr. Pearce. It seems to me that if the pressure at the end of a feeder, having a 4 per cent inductive drop at full load, is to disappear, then the fault current must necessarily be 25 times the full load and not 20 times as stated by Mr. Pearce. Moreover, it must be remembered that, unless all three phases have been short-circuited simultaneously, the three line voltages will not disappear and, as shown in Fig. 13, a relay with its pressure winding connected between the opposite phases will still receive more or less normal voltage. This feature was very clearly explained by Mr. Wedmore in his contribution to the discussion. At the same time, there are cases in which the feature whereby the reverse relay described in the paper can be caused to act at zero voltage, with a heavy current in either direction (say 20 or 30 times the relay setting) is occasionally of service. In this connection I may say that Dr. Gifford is correct in his assumption that this feature is obtained by an eddy-current effect, or more correctly by a transformer effect between two of the windings.

In reply to Mr. Taylor's question as to the reverse relay characteristics, I would say that the curve of Fig. 12 refers to a relay adjusted to give maximum sensitiveness at 45° (0·7 power factor) lagging, at which power factor the test was made. Consequently, with a power factor of 0·25, as specified by Mr. Taylor, the tripping currents given in the curve would be doubled. As explained by Mr. Wedmore in his contribution to the discussion, a relay so set will be operative on forward currents of very low leading power factor and will be inoperative on reverse currents of very low leading power factor. Such settings have been proved in practice to be in every way satisfactory.

The protective system shown in Fig. B of Mr. Pearce's remarks is an interesting method of applying leakage tripping to parallel feeders, but it appears to suffer from the serious objection that it fails to distinguish between the sound and faulty feeders, both being isolated in the event of a fault in either. I am pleased to hear from Mr. Pearce that there is a prospect of the settings of Merz-Price generator protective gear being reduced below the 40 per cent mentioned in the paper, but to judge from the figures called for in recent contracts this latter figure still seems to be about right. I would take this opportunity of pointing out that although an excessive earth current is a disadvantage, at the same time, for differential reverse relay protection (Figs. 8 and 9) it is not well to cut it too fine and, as the result of discussing this question with various engineers, I have somewhat increased the figures given in the proof of the third column of the table on page 405 of my paper.

Mr. Powell refers to the Waters reverse relay protection. I did not allude to this in the paper for the reason that, depending as it does upon current only for its sense of direction, its usefulness is limited, like all other similar devices, to the outgoing ends of independent parallel feeders. At the substation ends of such feeders, and at each end of interconnectors and ring-main feeders, voltage-controlled relays are required and the arrangement then becomes almost identical with that of Fig. 8 in the paper. This consideration also rules out a number of other schemes which have been proposed—several very ingenious ones of Mr. McColl's, for example.

With regard to the question raised by more than one speaker as to the impossibility, no matter what precautions are taken, of ensuring that a circuit breaker shall not be called upon to open at the peak of the current curve shown in Fig. 5, I would suggest that the existence of this possibility, which must of

course be recognized, ought not to blind one to the undoubted advantage of obviating such an occurrence whenever it can be done, which is probably in nine cases out of ten.

No one will quarrel with Mr. Cowie in his desire for the installation of as few current transformers as possible, but I would again urge the advisability of keeping protective-gear transformers separate from measuring-instrument transformers, owing to the chance of interference with the secondary connections of the former. I would add that the greatest care should be taken with the relay connections in view of the very heavy secondary currents which may flow in the event of severe short-circuits. Whilst on the subject of instrument transformers, I should like to suggest that the risk of breakdown to potential transformers would be greatly reduced if, instead of being connected between phases, where they undoubtedly form a weak link in the system, they were star-connected on the high-tension side (but, of course, not earthed) and delta-connected on the low-tension side. In this way each potential transformer could be kept entirely within the cubicle allotted to its particular phase instead of, as at present, linking two phases together and being, as it were, an outcast from both. In view of the necessity for potential transformers for use with watt-hour meters, voltmeters, etc., quite apart from relays, the question is, I think, one well worthy of the consideration of switchgear designers.

In conclusion I have to thank the various speakers for their many valuable suggestions and can only hope that the proposals contained in the paper may prove of use to some of those station engineers who are reconsidering their protective gear.

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NOTES ON OPERATING A BY-PRODUCT PRODUCER GAS PLANT FOR POWER AND HEATING.

By W. H. PATCHELL, Member.

(*Paper received 29 December, 1919; read before* THE INSTITUTION 11 *and 18 March, before the* NORTH-WESTERN CENTRE, 9 *March, and before the* SOUTH MIDLAND CENTRE, 31 *March,* 1920.)

Apart from the three classical papers by Mr. H. A. Humphrey,* there are some scattered articles but nothing generally and conveniently accessible on this subject. It is thought, therefore, that some notes on the lay-out and operation of a modern by-product producer gas plant and accessories, and the use of the gas, would be acceptable.

The plant to be described arose out of an investigation as to what was the best form of prime mover for the Hoffmann Manufacturing Company, Ltd., to adopt in the next extension of their works. The investigation was made in 1915. At that time Messrs. Hoffmann were using a steam engine and boilers, suction gas engines with anthracite producers, Diesel oil engines, and furnaces—heated in some cases by bituminous coal, and in other cases by anthracite producer gas. Consideration of the then costs of coal and oil, and the fact that the probable user of fuel in connection with extensions then in view would be equivalent to about 60 tons of coal a day, the choice fell on a by-product recovery producer gas plant. The plant selected was on the "Lymn" system which, although much like the better-known "Mond" system, differs from it in important constructional and operating particulars.

It was arranged to put down the plant in 30-ton units, as, owing to the war, it was thought that the growth of the business, and consequently the need for the complete 60-ton plant, might be indefinitely postponed. The first unit was ordered in July 1916, but, due to constructional delays, it was not put into operation until August 1917.

A sudden increase in the business necessitated the ordering of the second unit shortly before the first was put to work. The complete 60-ton plant has now been in operation since March 1919, but has not yet been worked up to its full capacity.

* "Mond Gas Producer Plant," Institution of Civil Engineers, 1897; "Power Gas and Large Gas Engines," Institution of Mechanical Engineers, 1901; "Generation and Distribution of Producer Gas in South Staffordshire," Institution of Civil Engineers, 1912.

DESCRIPTION OF PLANT.

Gas plant.—Before describing the gas plant in detail it may be well to outline some of the essential points in the operation of a by-product recovery gas plant.

The ordinary non-recovery gas producer is supplied with air mixed with a small proportion of steam; the latter is necessary for obtaining good-quality gas and also to prevent the formation of clinker. The ammonia formed under these conditions is, to a great extent, destroyed again owing to the high temperatures existing in the producer.

In a by-product recovery producer it is necessary to prevent the destruction of the ammonia, and this result is obtained by introducing a large quantity of steam with the air into the producer; this has the effect of facilitating the formation of ammonia and preventing its destruction by keeping the temperatures in the producer comparatively low.

The amount of steam introduced varies according to the kind of coal in use; from 2 to 2½ lb. of steam per pound of coal gasified may be taken as an average figure.

The provision of so much steam is a serious item in the cost of production, so that as much steam as possible is obtained by utilizing the sensible heat of the gases. The method adopted is to cool the gases by contact with water, and to heat up and saturate the air with the hot water so obtained. The process is continuous, the water coming successively into contact with the gas and the air. This results in approximately 0·75 lb. of steam being picked up by the air for every pound of coal gasified, which corresponds to a temperature of about 68° C. saturation.

The balance of steam required, which varies according

to the kind of coal in use, is from 1·25 lb. to 1·5 lb. per pound of coal gasified and is blown into the saturated air, thereby increasing the saturation temperature to from 82° C. to 84° C. Although the calculated amount of steam carried forward with the air may be 2¼ lb. per pound of coal gasified, it is doubtful if such is actually the case.

Steam was required for other purposes outside the gas plant and, in accord with the usual and economical practice, a superheater was included as part of the boiler plant. When using the superheated steam for the gas plant it was found that the air was not saturated to the extent indicated by the thermometer. In order to obtain steadier operating conditions the pipe arrangement was changed and saturated steam was used for the gas plant in place of superheated.

The quantity of steam required for this purpose, and on the plant generally, has a most important bearing on the net coal consumption, so, in order to obtain some data, arrangements were made to isolate one boiler temporarily for this purpose only, and two tests were made, the results of which are given under "Operating Results" on page 423.

The introduction of such highly saturated air into the producer would result in cooling the fuel bed below a good working temperature, and to prevent this a regenerator is provided wherein the temperature of the air and steam mixture is increased to about 220° C. before it enters the producers, the necessary heat being obtained from the sensible heat of the hot gases leaving the producer.

The ammonia having been formed passes off with the gases which, after preliminary cleaning and cooling, are brought into contact with sulphate of ammonia liquor containing a slight excess of acid, the excess acid combining with the ammonia in the gas to form sulphate. The process is continuous and periodically, when the liquor is sufficiently concentrated, a portion is drawn off and sent to the stock liquor tanks, water and acid being added to take its place.

"Lymn" system.—Fig. 1 shows a diagrammatic view of a plant on the "Lymn" system. It may be said at the outset that the whole of the vessels on this system are worked under static conditions, all the washing being done by the movement of the gas and water, unassisted by mechanical means as in the case of most other gas washers.

Fig. 2 shows the general lay-out of the plant. The first two producers installed were those next the river. When the second half of the plant was put up a large "bus" pipe was arranged connecting the two halves of the plant, so that gas from the first pair of producers could be passed through the second set of washers, or from the second pair of producers to the first set of washers, or the whole plant could be run in parallel.

The use of mechanical grates for the producers was considered, but they were not adopted as it was intended to use good coal, and as the number of producers was small it was thought that the extra capital outlay for a mechanical grate would not be justified. Subsequent experience with the "controlled coal" that had to be used went to show that mechanical grates would have been a distinct advantage.

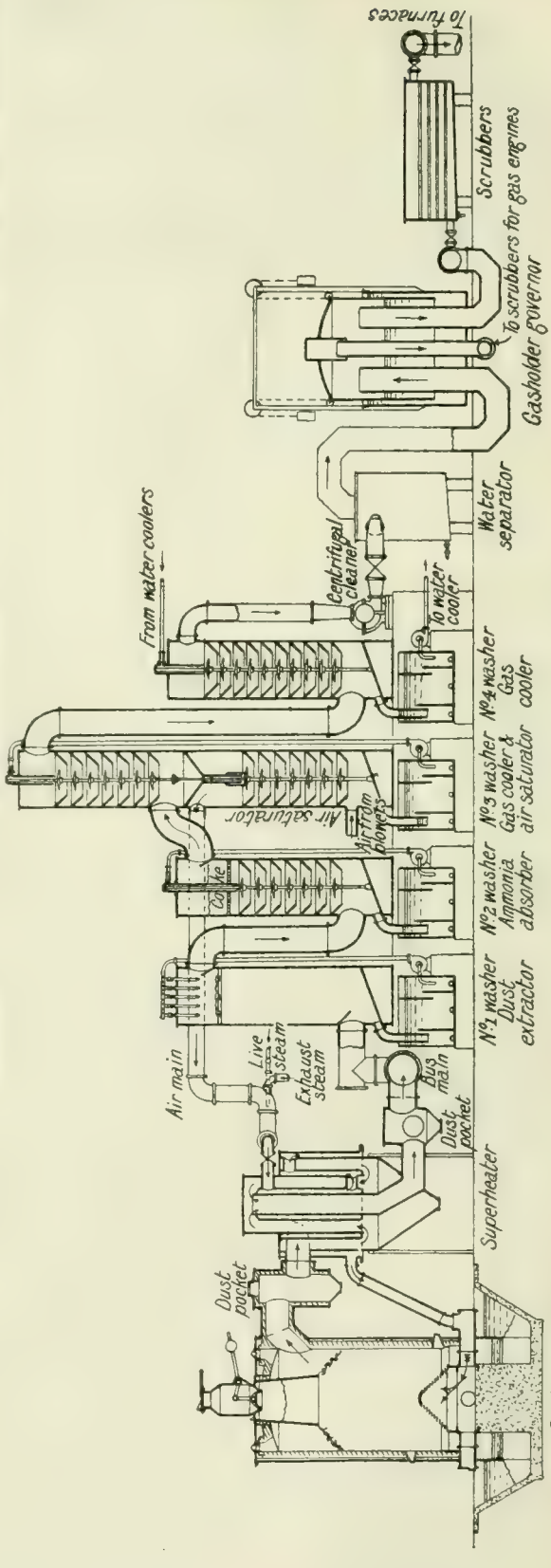


FIG. 1.—Sectional diagram of Lymn gas plant.

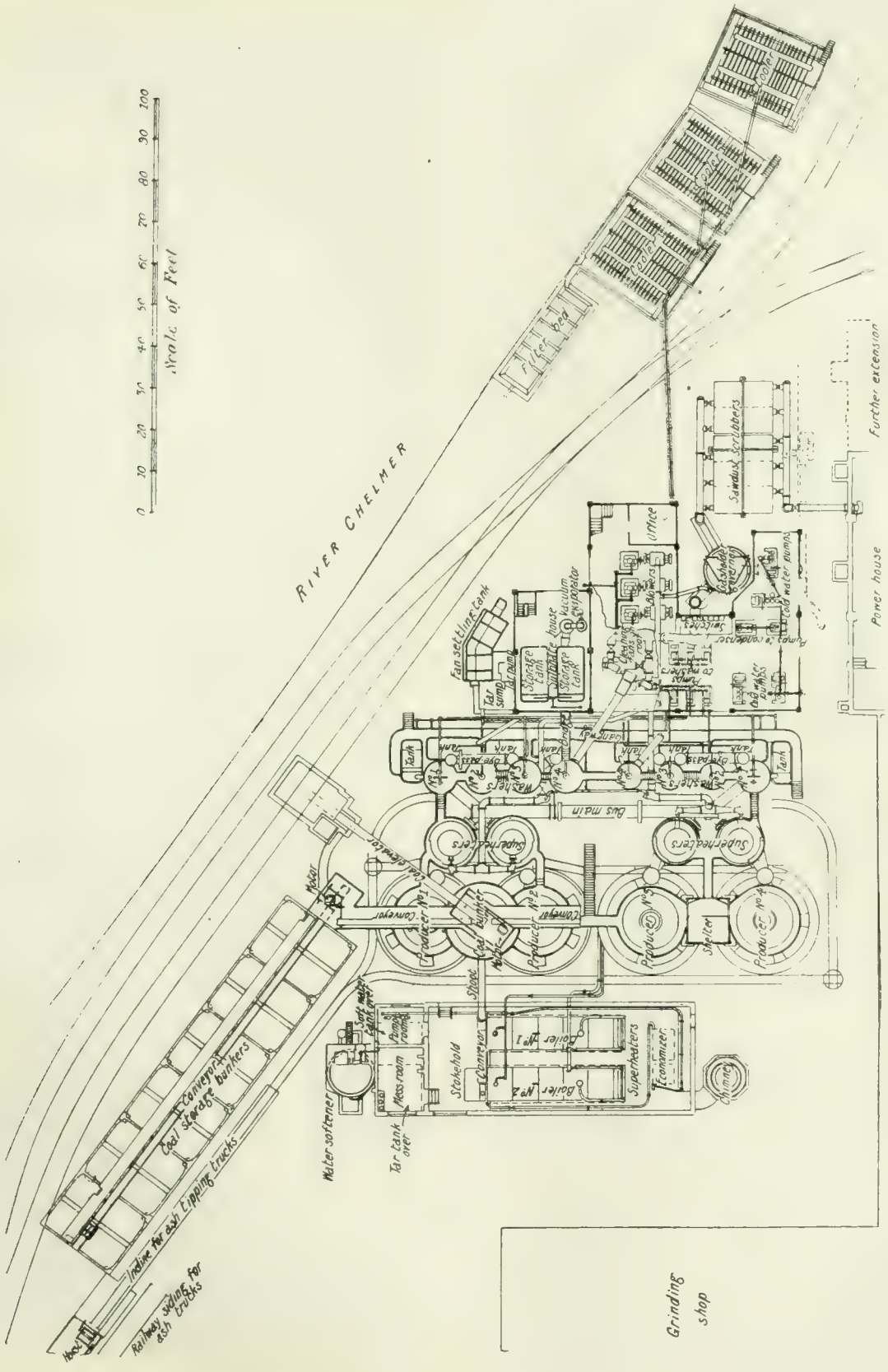


FIG. 2.—Arrangement of Lynn gas plant.

The air, which is supplied by Samuelson blowers, enters the lower part of No. 3 washer, called the air saturator. It will be noted that the upper part of No. 3 is divided off by a diaphragm, the only connection between the two being through a water seal. The water, which is made hot by contact with the gas in the upper part of the vessel, passes through this seal into the air saturator and there meets the air from the blowers. The additional steam which is necessary for a recovery plant is blown into the air main between the air saturator and the regenerator. The warm saturated air is then passed through the regenerator which stands next to the gas producer

The regenerator, sometimes called a superheater, consists of a nest of concentric cylinders so arranged that the hot gases from the producer and the saturated air pass in counter current. Owing to the large amount of steam which is blown into the gas producer with the air, the working temperature is comparatively low. The gases leave the producer at the top and pass into the regenerator above mentioned, where their sensible heat is given up in part to the air and steam.

The hot gas leaving the regenerator is then passed through a dust trap before it enters the vertical dust washer No. 1, in which the remaining dust is removed as sludge by the washing water. From the top of the dust washer the gases pass down to the bottom of No. 2 washer. In their upward flow through this washer they are brought into intimate contact with a solution of sulphate of ammonia containing a slight excess of sulphuric acid which absorbs the ammonia from the gas.

After the ammonia has been absorbed in No. 2 washer the gas passes through the upper part of No. 3 washer, thence down to the bottom of, and up through, No. 4 washer.

It will be noticed that the design of the Lymn washers differs from other types in that they are free from obstructions in the shape of packing boards or tiles, and from moving parts. The apparatus consists of several vertical cylindrical chambers, No. 1 of which is simply fitted with water jets at the top which fill the vessel with spray through which the gas passes in an upward direction and is thereby washed. Nos. 2, 3, and 4 contain a series of truncated cones. Axially placed in the centre of the apparatus a vertical shaft carries a number of fixed discs opposed to these cones. The water entering at the top is distributed on the topmost disc from which it flows in a film or sheet on to the surrounding cone, thence it falls on to the next disc and so on to the bottom of the washer. The gas passes upwards, counter-currentwise, through the sheets of falling water. By this means the gas and the washing liquids are brought into intimate contact, with a minimum expenditure of energy.

The liquor from each of the various washers falls into its respective tank, from which it is drawn by a centrifugal pump and circulated again through the washer, except in the case of No. 4 washer, the hot water from which is put through a water-cooling plant before being re-circulated.

In view of the difficulty in obtaining pure lead and its cost at the time the plant was installed, it was decided to depart from the usual practice and not line the ammonia absorber with lead. Several plants had previously been constructed with steel absorbers, and in one case a Lymn plant, erected in Germany, had been at work for over three years prior to the war, without any corrosion taking place.

The gas, after leaving the final cooler No. 4, is passed through two Jenkins centrifugal gas cleaners. These consist of 25 in. diameter centrifugal fans with impellers of a somewhat crude shape; each of them is capable of handling continuously 4,500 cubic feet of gas per minute against a pressure of 5 inches of water when running at from 1,450 to 1,650 r.p.m.

The amount of power taken is 10 to 12 b.h.p. for each fan with water injection. Approximately 500 gallons per hour of cold water is injected into each fan, depending on the class of coal in use and the atmospheric conditions. The tar and water drain away from the outlet pipes of the fans to a settling tank from which the tar is skimmed off.

The gas, after leaving the fans, passes through a water separator of the cyclone type before it goes into the gasholder governor, which is so arranged that, in the event of the gas failing, the supply to the gas engines is cut off before that to the furnaces. This prevents any suction caused by the engine coming on the furnaces, which might lead to an explosion should the gas come on again suddenly.

Gas intended for use in the engines is then passed through sawdust scrubbers to extract the last traces of tar. The scrubbers have been arranged on the usual system in which the gas passes upwards. With a view to facilitating cleaning, arrangements have been made to pass the gas either upwards or downwards in some of the last scrubbers installed. With an upward-flow scrubber the dirtiest material is at the bottom of the scrubber and, when it is necessary to change it, the cleaner layers at the top have to be removed for the sake of getting at the dirty material. In a downward-flow scrubber the dirtiest material is at the top and can be removed without disturbing the whole of the packing material from the scrubber.

Each scrubber box is 13 ft. 6 in. × 6 ft. × 5 ft. deep, fitted with four sets of trays which are packed with sawdust and shavings, finishing off with a blanket or sacking to prevent any of the packing material being carried forward by the gas. Drains are provided to carry off any water or tar collecting in the bottom of the box.

It was expected that the centrifugal fan cleaners would have made the gas sufficiently tar free to be used on the furnaces without the interposition of sawdust scrubbers, but it was found that the small burners and pipes in use led to a small amount of tar condensing in the gas cocks and connections which had to be cleaned out periodically. It was decided therefore to install scrubbers for the whole of the gas.

In large metallurgical furnaces where the burners are formed of refractory nozzles, and the gas is conveyed in large pipes, such freedom from tar would not be necessary. In the present case the furnaces are supplied through pipes down to $\frac{3}{4}$ in. diameter, and it was not deemed wise to run any risk of blocking them.

Concentrated liquor produced in the ammonia absorber is by-passed from time to time to two stock tanks at the top of the evaporator house. From these tanks it is drawn as required into a vacuum evaporating pan made by Messrs. Fullerton, Hodgart and Barclay. The vacuum is obtained by a Ledward and Beckett ejector.

Sulphate of ammonia evaporators are generally constructed of copper or bronze. The Lymn practice has been to make the casing of chemical cast iron with the boiling tubes and tube plates of a copper alloy. At the time the plant was ordered it was impossible to obtain bronze tubes. A tube plate of mild steel and solid drawn steel tubes were used on account of expediency. The life of the tubes (No. 13 S.W.G.) and tube plate was 10 months, after which the tubes gave out completely. New tubes and tube plate were fitted, the tubes being $\frac{1}{4}$ in. thick; these have been in operation 10 months. Corrosion has taken place at the top end of the tubes and also in the top tube plate round the tubes; it is hoped to overcome this difficulty as the other parts of the plates and tubes are in good condition.

Sulphate of ammonia crystals from the evaporator are dried in a hydro-extractor, made by Messrs. Watson and Laidlaw, consisting of the usual revolving perforated copper basket suspended inside a mild steel casing lined with chemical sheet lead.

Sulphuric acid stock.—The sulphuric acid is delivered in tank wagons and discharged by an air lift into a steel tank on the top of the pump room from which it runs by gravity through lead pipes to No. 2 washer (ammonia absorber) tanks.

Coal store.—Coal is delivered by railway trucks to the boot of a Gibbons Bros. bucket-type elevator, which delivers it on to a band conveyor supplying the 30-ton pockets over the producers, or by a second band conveyor which carries it into the ferro-concrete storage bunker, constructed by Stuart's Granolithic Company. This bunker holds 1,200 tons, and consists of six 200-ton pockets raised on columns sufficiently high to allow 5-cwt. trucks to run underneath.

The band conveyor feeds a push-plate conveyor which delivers the coal into any of the 200-ton pockets as required. When the pockets are empty there is a distance of 40 ft. between the conveyor outlets and the bottom of the bunker. The coal, already small, would have been still further reduced in size if allowed to fall from such a height. To prevent this a series of shutes at an angle of 45° are provided, and these carry the coal down to the bottom of the bunker which is also formed at an angle of 45°. By this arrangement the coal is stored practically as received, and during filling operations very little dust rises. The bunker is covered with a roof for protection from the weather.

When it is necessary to draw from the storage bunker, the coal is run through valves at the bottom of the bunker into the trucks and thence tipped into the foot of the elevator.

Ash handling.—The ashes and clinker from the producer lutes are drawn out by long shovels and rakes on to the ground round the producers, which is slightly graded to allow the water to drain back into the lutes. The ashes are then loaded into 5-cwt. trucks running on a narrow-gauge line, pushed by hand a short distance to an incline, up which they are hauled by a small electric winch and tipped into a railway truck or cart according to their destination.

Gas Engines.

Messrs. Hoffmann decided that power units of about 500 b.h.p. would be the most suitable size. The relative merits of vertical and horizontal types were carefully reviewed. The type of engine selected was the multi-cylinder horizontal "Otto" manufactured by the Premier Gas Engine Company, Ltd. The floor space occupied is greater than that taken up by a vertical engine, but the sacrifice in floor space is set off by the greater accessibility of the horizontal type.

Another point of difference between the vertical and the horizontal type of gas engine is the speed. The majority of vertical engines run at 250 to 300 r.p.m. In the "Premier" engine the speed adopted is 190 r.p.m. which results in much sweeter working and a quieter engine-room. This four-cylinder four-crank engine is naturally somewhat heavier than a six- or eight-cylinder high-speed engine and, to obtain the necessary cyclic regularity for parallel running, a heavy flywheel is used.

A spring-type governor is provided which controls a throttle valve on the gas supply to the engine. The throttle-valve spindle is fitted with a quadrant and pointer showing to what extent the valve is open. With the aid of this the attendant can easily tell if the governor is working freely. It also gives an indication of the quality of the gas by its position as compared with the load.

The air supply is not controlled by the governor, but means are provided for adjusting the amount of air when tuning up; under running conditions it is found that gas governing alone is quite sufficient.

Exhaust boilers.—Each gas engine is fitted with an exhaust boiler supplied by Messrs. Ruston and Hornsby, Ltd. In the case of the first two engines the boilers were installed without water heaters. Water heaters were, however, added to the boilers connected to the later engines. In order to keep down the temperature of the engine-room and to save heat, the exhaust pipes between the engines and the boilers were lagged. Under these conditions the pipes got red hot and were unsafe, so that the lagging had to be removed and the economy due to it on the heat balance sacrificed for other considerations.

In the first two engines installed the exhaust was connected direct to the boiler without a by-pass, so that in the event of the boiler having to be opened the engine would be on stop. This risk, as will be seen from the operation figures given on page 424, was comparatively small; but it was decided in the case of the other four engines to provide a by-pass and, subsequently, the first two boilers were also by-passed.

Dynamos.—Messrs. Hoffmann's works, at the time that the extensions took place, were driven by direct current at 110 volts, and, although it was recognized in the first extension that a higher voltage would be more suitable, it was decided that the first two dynamos should be 110-volt d.c. machines, so as to avoid installing

new motors and cables and the nuisance of changing the existing plant.

When the second instalment of plant was put in hand it was decided to use a pressure of 220 volts, as the current was intended for new shops, for which new motors, cables, etc., had to be ordered in any case.

All the dynamos were supplied by Messrs. Crompton & Co., and are open type, direct current, shunt wound interpole, 360 kw. machines, running at 190 r.p.m. They are provided with a "Hoffmann" roller outer bearing supported in a cast-iron pedestal on a "U" bedplate, and the armature shaft is bolted direct on to the engine flywheel. This makes a very neat and compact arrangement and has run very well.

and of skilled workmen, the completion of the work was delayed and the cost increased.

Table 1 shows the outlay per kilowatt.

The first installation consisted of a Lymn gas plant capable of gasifying 30 tons of coal per 24 hours, sulphate of ammonia evaporating plant, two 500-b.h.p. Premier-Crompton generating sets, Lancashire boiler, superheater, economizer, chimney, pumps, pipes, feed pumps, 600-ton coal-storage bunker and coal-handling plant, etc.

The second plant was a repetition of the first, except that four 500-b.h.p. Premier-Crompton sets were provided and the gas and electric supply had to be carried considerable distances.

TABLE 1.

Capital Cost of Plant per Kilowatt.

Date	First Plant 1916	Second Plant 1917	Average
	£	£	£
Lymn gas producer plant, without buildings or foundations	12·20	14·26	13·230
Foundations and buildings for Lymn gas plant	2·45	2·23	2·340
Coal storage and coal-handling plant (600 tons each)	2·76	2·69	2·725
Building of power houses A, B, and C, and engine foundations, cranes	7·30	9·05	8·175
Gas engines, gas pipes, water and compressed air pipes, compressors in power houses	7·75	12·20	9·975
Exhaust boilers with steam, water and exhaust pipe connections	1·14	1·99	1·565
Generators, switchboards and connections	5·70	5·98	5·840
Lancashire boilers, chimney, boiler house and coal-handling plant	1·68	1·60	1·640
Total cost per kw.	£40·98	£50·00	£45·49

Boiler plant.—In addition to the steam required for the gas plant a large amount is required for heating and domestic purposes in the works, more especially in the winter. This is provided in part by the exhaust boilers fitted to the 500 b.h.p. gas engines. To meet the remaining call for steam two Lancashire boilers were provided, one with the first 30-ton unit and the other with the second.

The Lancashire boilers, 9 ft. diameter × 30 ft. long, were made by Messrs. H. & T. Danks (Netherton), Ltd., and are fitted with Hodgkinson's mechanical stokers, a Green's economizer, a Sugden superheater, and feed regulators. These call for no special remarks except in reference to tar burning, which is dealt with on page 425.

One of Paterson's "B" type cold-process water-softening plants is installed for dealing with the whole of the water required for steaming purposes, as the water available was not suitable. By the use of lime in this plant the hardness of the water is reduced to 3 degrees "Clark" approximately, and the boilers are kept free from scale.

CAPITAL COSTS.

Owing to the war the cost of the plant was much above pre-war rates; also, due to the shortage of material

OPERATING RESULTS.

Fuel.—Owing to war conditions the supply of coal was very uncertain and, in consequence, various kinds were used. In January 1918 some 795 tons of coal of nine different sorts were gasified. By December 1918 deliveries had improved and were only of five different sorts. It will be readily understood that such variations do not improve working conditions.

The ashes withdrawn from the producers during 1918 averaged a carbon content of 11·8 per cent, which represents 3·23 per cent of the therms * in the coal.

The results given in this paper were obtained without special arrangements and under normal conditions, and can be taken as typical commercial results. No effort has been made to obtain special test figures which are not realized under ordinary working conditions.

Steam required for gas plant.—The amount of steam required is considerable, mainly for use in the producers and for evaporating the sulphate liquor. In addition to these uses there are tar troughs to be heated, tar tanks to be kept at such a temperature that the tar for burning is quite fluid, and various incidentals about the plant. In order to obtain some accurate figures of the

* Throughout this paper the word "therm" is used for "British thermal unit."

steam consumption one Lancashire boiler was isolated and used for steam supply for the gas plant only, and a test extending over one week was carried out.

Coal gasified	136 tons 10 cwt.
Water evaporated	447,600 lb.
Coal used in boiler	24 tons 7 cwt.
Tar used equal to 6 tons coal ..	6 ,, 0 ,,
Coal equivalent used on boiler ..	30 tons 7 cwt.

Equal to 22·25 per cent of the coal gasified.

Amount of sulphate salts made: 6·256 tons, or 102·6 lb. per ton of coal gasified.

A second test under similar conditions showed :—

Coal gasified	145 tons 15 cwt.
Coal equivalent used on boiler ..	33 ,, 18 ,,

Equal to 23·25 per cent of the coal gasified.

These figures are rather high, as the Lancashire boiler available for the test is capable of evaporating three times the amount of water required, and was not working therefore at an economical rate. As, however, the above tests were taken in May and June, and the heat losses would be slightly greater during the cold months of the year, the costs given later allow for coal for steam raising at 25 per cent of the coal gasified.

A charge of approximately 25 tons of coal for steam required for the producer and gas plant only, for every 100 tons of coal gasified, is a heavy item in working costs and one that must always seriously affect the use of by-product producer plants.

Messrs. Hoffmann recognized that their conditions would be favourable for adopting this type of plant, coupled with an installation of exhaust boilers. By using these boilers and burning tar 75 per cent of the 25 per cent of the coal required for the gas plant is provided, and the actual coal required for gas plant steam is reduced to 6·25 per cent of the coal gasified.

Coal consumption and thermal efficiency.—As already pointed out the coal supply varied very considerably, consequently the results are not so good as they would have been if one kind of coal only had been used. It is a well-recognized fact that a mixture of coals in a producer leads to difficulties unless a suitable choice can be made. In the plant under review it was a case of " Hobson's choice."

Figures for six months' operation of one 30-ton gas plant supplying gas for two engines and furnaces may be analysed as follows to show how the efficiency would appear if all the gas were used for power. The result is summarized in Table 2.

During this period the total coal gasified was 3,255 tons, giving an average load of about 75 per cent during operating hours of the plant. Of the total amount of gas made 42·7 per cent was used for the engines and 57·3 per cent for the furnaces. For this purpose the whole of the steam raised by the exhaust boilers is credited to the gas engines, and the tar is allocated in proportion to the gas used by the engines and the furnaces respectively.

The figures used for converting the work done by the exhaust boilers and by tar to a common coal equivalent are :—

Exhaust boilers ..	1 b.h.p.-hour	= 2 lb. steam
Lancashire ,, ..	1 lb. coal	= 6 ,, ,,
,, ,, ..	1 lb. tar	= 7½ ,, ,,

TABLE 2.

Power-plant Coal Consumption.

Coal Gasified in Producers		Coal if 25 per cent is Required to Provide Steam	Coal Gasified plus Coal for Steam Making		Amount of Coal Saved		Surplus Steam used for Manufacturing Purposes	Actual Coal to be Debited to Power Plant		Load Factor Gas Engines	Overall Electro-Thermal Efficiency
Total	Per kw.-hr.		Total	Per kw.-hr.	by Exhaust Boilers	by Tar Burnt		Total	Per kw.-hr.		
tons	lb.	tons	tons	lb.	tons	tons	tons	tons	lb.	per cent	per cent
					379·75	114·7					
1,390	1·7	347·5	1,737·5	2·12	494·45 tons		146·95	1,243·05	1·51	73·6	19·9

Based on these equivalents the amounts of coal saved during the six months by the use of the exhaust boiler and by burning the tar are :—

By exhaust boiler	379·75 tons
,, tar burning	114·70 ,,
Total	494·45 tons

During the period the two engines generated 1,834,375 units, giving an engine load factor of 73·6 per cent on running hours.

The above table shows the actual coal gasified in lb. per kilowatt-hour ; also what it would have been on the 25 per cent basis if all the steam for use on the gas plant were made by coal-fired boilers ; finally, the equivalent coal for the amount of steam actually made by the exhaust boilers and by tar burning, and its effect on the coal consumption per kilowatt-hour. The net amount works out at 1·51 lb. per kilowatt-hour and is the figure used in the working costs given later.

The average calorific value of the fuel over this period was 11,333 therms per lb., giving an overall thermal efficiency of

$$\frac{\text{Therms per kw.-hour at switchboard}}{\text{Cal. value} \times \text{net coal used per kw.-hour}} = \frac{3412 \cdot 5}{11{,}333 \times 1 \cdot 51} = 19 \cdot 9 \text{ per cent}$$

As will be seen from the table more steam is raised by the exhaust boilers than is required to make gas for the engines. In other words exhaust boilers in connection with gas engines at a gas works would provide all the steam required for the producers, working under

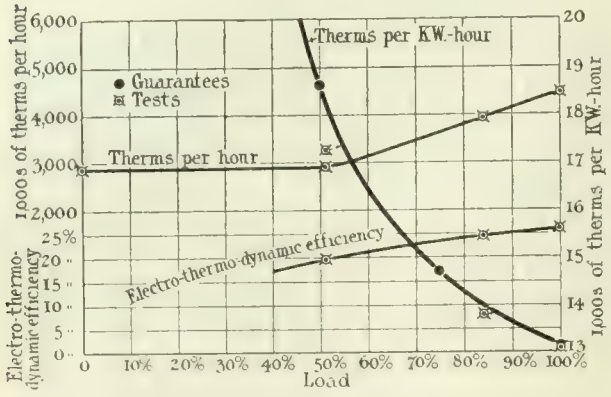


FIG. 3.—Heat consumption curves of 500 b.h.p.—340 kw. "Premier-Crompton" set.

by-product recovery conditions, necessary to provide the gas for the engines when working on a good load factor.

Gas consumption and quality.—Owing to the large quantity of gas made, 130,000 to 140,000 cubic feet per ton of coal gasified, it was found that the cost of metering apparatus to record the whole of the gas made was too high to warrant its installation.

A rotary meter capable of measuring the amount of gas taken by two "Premier" engines was purchased and provision made for fixing it in various parts of the plant, so that tests could be made in the different engine-rooms. The amount of gas used on the Premier engines has been calculated from the results so obtained.

The test for the correctness of the meter at the makers' works was as follows :—

At 80,000 to 20,000 cub. ft. per hour	.. correct
,, 10,000 to 8,000 cub. ft. per hour	.. 2 % slow

Fig. 3 gives curves of the heat consumption guaranteed, the results of tests of the same, and the thermal efficiency of the Premier-Crompton sets.

The working costs given later were calculated from the guaranteed curve plus an additional allowance for preliminary runs and starting up; consequently the figures are on the safe side.

To obtain a record of the calorific value and of the composition of the gas made, two methods were adopted. A recording calorimeter of the "Sarco" type was installed. This apparatus shows the calorific value of the gas and records continuously any variations that may occur therein. It is a very useful instrument but requires checking from time to time.

For more detailed tests and analysis an aspirator is used which draws off gas over a long period. The sample thus obtained is analysed in a Hempel's absorption pipette with suitable re-agents.

Table 3 gives the results over a period of 3 months, from which it will be seen that the variations are very slight considering the different qualities of coal used.

Tests of the engines have been made, representative figures of which are given in Table 4.

The efficiency of the Crompton dynamos on a "Hopkinson" test was found to be :—

Full load	92 per cent
Three-quarter load	91 ,,
Half load	90·5 ,,

As regards operating, the engines have run with the regularity and the freedom from trouble of a good steam engine.

TABLE 3.

Average Analysis of Producer Gas Made.

Date, 1918	Number of Tests	Average Period covered by each Sample	CO_2	O	CO	CH_4	H	N	Total Combustible	Calorific Value per cub. ft., net
		hours	per cent	per cent	per cent	per cent	per cent	per cent	per cent	therms
Three months..	42	12·6	15·8	0·15	10·68	2·59	26·6	44·1	39·87	139·5
Highest individual readings ..			17·4	0·5	12·50	3·00	28·4	48·3	42·6	150·6
Lowest individual readings ..			12·2	—	9·10	2·10	24·8	41·6	37·4	130·1

The total operating hours for 1918 were :—

Engine	Hours Run	Compulsory Stoppages
No. 9	6,291	52¾ hours, of which 43 hours was due to exhaust boiler
No. 10	6,588	32½ hours

Those who are interested in the compression-pressure question may note that the pressure in these engines is 120 lb. per square inch.

Exhaust boilers.—Tests of these have been made with and without the water heaters. Specimen tests are given in Table 5.

Sulphate of ammonia recovery.—The amount of sulphate recovered depends on the amount of nitrogen

in the coal, this is usually in the neighbourhood of 1·3 per cent from which theoretically 136·5 lb. of sulphate should be made; actually, as will be seen from Table 6, some 90 lb. is recovered—an efficiency of about 65 per cent. The sulphate is of a good light grey colour, and averages over 25 per cent NH_3.

Owing to the varying qualities and quantities of coal, and the size of the stock tanks, it has been impossible to obtain a straight test.

Use of tar.—The amount of tar produced in the process varies with the class of coal used; 5 to 7 per cent of the weight of the coal is a normal figure for dry tar. The tar as made contains anything up to 40 per cent of water.

There is a good market for gas works tar, and no difficulty generally occurs in disposing of it. Producer tar, however, is of a different quality and is not usually acceptable to distillers of gas tar. Where the quantity of tar to be handled is sufficiently great to pay for distillation, it may be economically dealt with in this way; but it must be remembered that tar distillation requires special care and attention, particularly when it may be emulsified with water, and if the quantities to be handled are not sufficient to pay for such care and attention the result will be disappointing.

Full consideration of the matter led to the use of the tar recovered, which amounts to about 150 lb. per ton of coal gasified, in the boiler furnaces. Jets of the Ker-

TABLE 4.

Test of Gas Engine and Generator.

Engine Set, Number.	Load Factor	Load	Generator		Load	Gas Engine		Calorific Value of Gas per cub. ft., net
			Gas per kw.-hour	Heat per kw.-hour		Gas per b.h.p.-hour	Heat per b.h.p.-hour	
	per cent	kw.	cub. ft.	therms	b.h.p.	cub. ft.	therms	therms
12	102	350	93·57	13,062	510	64·24	8,968	139·6
11	84	285	102	13,759	420	69·5	9,368	134·79

TABLE 5.

Tests of Exhaust Boilers using the Exhaust Gases from a 500-b.h.p. "Premier" Gas Engine.

Engine Set, Number	Load	Heating Surface			Steam Pressure	Evaporation per b.h.p.-hour		Temperature of Exhaust Gases			Load Factor
		In Boiler	In Water Heater	Total per b.h.p.		Actual	From and at 212° F.	Entering Boiler	Leaving Boiler	Leaving Heater	
	b.h.p.	sq. ft.	sq. ft.	sq. ft.	lb. per sq. in	lb.	lb.	°C.	°C.	°C.	per cent
9	471	523	None	1·05	53·7	1·91	2·16	560	291	—	94
11	420	523	57·5	1·16	43	2·15	2·5	477	198	180	84

TABLE 6.

Sulphate of Ammonia

Average amount recovered per week on standard basis, 24·5 per cent NH_3.

Weeks	Coal Gasified	Sulph. Am. recovered	Sulph. Am. per Ton of Coal	Nitrogen in Coal	NH_3 recovered	Actual NH_3 in Sulph. Am.
	tons	tons	lb.	per cent	per cent	per cent
26	134·3	5·21	87	1·285	64·2	25·29
13	150·1	6·11	91·03	1·32	65·6	25·39

A recovery of 65 per cent of the nitrogen in the coal appears, at first sight, rather low, but the difficulty in sampling must be remembered and a sample taken by the men who unload the trucks cannot altogether be relied on as showing the average of the bulk.

A more critical figure for the ammonia absorber efficiency is given in Table 7, which shows the amount of ammonia per cubic metre of gas when entering and when leaving the absorber, the actual ammonia not recovered being equal to only 4·25 per cent.

mode type were fitted, through which the tar is blown by steam over the grates. A compromise had to be arrived at as it was not possible to allocate any one furnace for burning tar only, and the arrangements had to be such that coal and tar could be burned at the same time. At times of light load it has been found best to shut the tar off and to run on coal only, keeping the tar for such times as a good coal fire can also be maintained, which not only protects the firebars from

TABLE 7.

Recovery of Ammonia in Absorber.

	Grammes NH_3 per cub. metre in the Gas		
	Entering Absorber	Leaving Absorber	Efficiency per cent
Average of 14 tests ..	2·73	0·116	95·75

the blast action of the tar jet but also facilitates the consumption of smoke. In this way the tar can be burned without smoke, but it requires watching. If the grates are allowed to run bare, and the tar jet deflected downwards, the grate bars may very readily be damaged.

Before deciding to burn it the question of distilling the tar was considered. A mixed sample was obtained and an analysis made, with the following result :—

Moisture	7 per cent
Crude oils up to 170° C.	2·6 ,,
Creosote between 170°–190° C. ..	17·5 ,,
,, ,, 190° C. to pitch ..	7·8 ,,
Pitch	65·1 ,,

On going into the question of distilling plant it was found that the cost of the same, and the labour in connection therewith, would not warrant its installation in view of the comparatively small amount of oil that would be recovered. The tar which comes off in No. 4 washer and the centrifugal cleaner undoubtedly contains more oils, but the quantity obtained is too small for distilling commercially.

Power-plant running costs.—Table 8 gives the cost per unit taken from the actual cost sheets for six months in 1918, including 10 per cent on the capital outlay.

The lubrication costs are rather high, due to the fact that at the period covered a system of forced lubrication was in use on two of the gas engines. Since then the arrangements have been altered and now the consumption of oil for lubrication on the gas engines has been reduced by 46 per cent.

The costs include the value of the current used in running the gas plant and auxiliaries which, during six months, amounted to approximately 8·5 per cent of the units generated. As, however, only about 42 per cent of the gas made was used for the gas engines the actual amount of current required for auxiliaries represents only 3·6 per cent of the current that would be generated if all the gas were used for that purpose.

The cost of the fuel if the above debit had not been made would be 0·160d. per unit, a difference of 0·006d. or 3·6 per cent.

NOTES ON OPERATING.

Producers.—These have worked very well, and although minor difficulties occurred during the first few months they have been overcome. The chief difficulty was due to the small coal and dust at first used. It was found that the circular overhead coal pockets and the cone valve on the feed hopper tended to separate the coal so that dust went to one side and the larger pieces to the other side of the producer, consequently the fuel burned unevenly and the side on which the larger fuel fell got much hotter due to the lesser resistance and freer passage for the air and steam.

In this connection it must also be borne in mind that all the stokers had to be trained from the beginning, and owing to the shortage of labour following mobilization no skilled stokers were available to give them the usual training. For a novice to handle a big producer with the long heavy pokers is strenuous work, but the difficulties were tackled very willingly and soon overcome, to such an extent that they were kept under until such time as regular deliveries of coal were made, when they disappeared.

Washer tanks.—The circulating tanks are provided with sloping bottoms so that the tar which settles in the water can run down and be drawn off when necessary. For Nos. 3 and 4 washers this worked very well, but with No. 2 the tar was sometimes too thick to run easily, and in No. 1 tank the amount of tar was usually small but mixed with a large proportion of dust and soot which blocked the tar outlets.

TABLE 8.

Power-plant Running Costs per Kilowatt-hour, Six Months, 1918. Including Credit for Sale of Sulphate of Ammonia and Debiting Cost of Sulphuric Acid.

Average price of coal	£1 8s. 11d. per ton.
Average price of sulphuric acid	£4 13s. 0d. ,,
Average price of sulphate of ammonia	£17 2s. 0d. ,,

Units from Switchboard	Fuel	Lubrication	Supervision and Labour	Repairs and Renewals	Charges on Capital, 10 per cent	Total	Load Factor
	d.	d.	d.	d.	d.	d.	per cent
1,834,375	0·166	0·058	0·159	0·130	0·207	0·720	73·6

The usual perforated scoops were provided for skimming the tar which floats off the surface of the water in the tanks. The use of them involved a good deal of labour and led to the development on the works of a better method. A sloping plate was fitted to the edge of the tanks at about an angle of 45° and dipping about 6 inches into the water. By using a flat scraper it was then possible to skim the tar off much more quickly and with less exertion.

Details of this kind appear insignificant but they make all the difference to the cleanliness and comfort in which the work can be carried on.

Corrosion.—In spite of the success which followed Mr. Lymn's use of non-lead lined steel vessels elsewhere, some anxiety was felt as to the result in this case and careful watch was kept, inspection being made whenever opportunity offered.

The reason why corrosion takes place in some cases and not in others does not yet appear to have been discovered, although many attempts have been made to solve the problem by chemists engaged on recovery plants. Apparently the composition of the coal has something to do with the matter. From the author's experience it would appear that when using mild steel plates very little corrosion takes place, unless the metal is also subject to either erosive action or is under stress. At such points corrosion may be rapid.

In the case of Messrs. Hoffmann's plant, ammonia recovery was not attempted until some weeks after the plant was started, in order that the interior of the vessel might get thoroughly coated with tar before any acid liquors were circulated. Beyond the failure of a few bolts and rivets there has been no trouble from corrosion.

Centrifugal fan cleaners.—These do their work well but too much is expected of them. The design of the fan is such that the tar and water driven out of the gas by centrifugal force are not thrown off clear but have to run down the casing and through the outlet with the gas before draining away, consequently the gas is liable to pick up some tar again.

A modification of the design which would allow the tar and water to get away from the system immediately it had been thrown out of the gas would make the machine more effective.

The action of the water in the tar fans is mechanical and, under present conditions, cold water is necessary to reduce the temperature of the gas and to condense the tar into such vesicles that it can be caught by, and separated out with, the water. If the washing water is cooled in towers the possible temperature of the return water is not really low enough to be thoroughly effective, so fresh cold water has to be brought into circuit and dirty hot water thrown away. The effluent, when handled in a coke filter, can be made perfectly satisfactory, but it leaves behind a tar laden by-product which is difficult to dig out of the filter beds and difficult to burn because it is saturated with water and coated with tar.

Sawdust scrubbers.—In town or coke-oven gasworks scrubbers packed with iron oxide are used, the action of which is chemical rather than mechanical, and the spent oxide residue has a trade value.

When sawdust scrubbers are used their function is purely mechanical. The removal of the tar-laden sawdust is an objectionable process and the dirty material is difficult to dispose of. Increasing the number of scrubbers only enables any box to run longer, as it decreases the rate at which the gas passes through it, and thus only postpones the dirty day. The final traces of tar are due to the lighter tars with low condensing temperatures, and it is therefore highly important to reduce the temperature of the gas before it reaches the scrubbers.

This all points, in the author's opinion, to the advisability of getting the gas temperatures down lower and catching the tar as pure as possible and free from sawdust, or coke filtering processes.

The P. and A. and various centrifugal types of machines have been used for town and coke-oven gas, but are not so successful on producer gas. It is hoped that the demand will justify research and experiments in this field, and will develop an apparatus which will be light in cost of operation and maintenance.

Electrostatic system of gas cleaning.—Having in mind some experiments conducted by Sir Oliver Lodge in 1905 in connection with fog dissipation, which, although quite successful on a laboratory scale, were found too costly to apply to a London fog, the author thought that something might have been done in this direction.

Sir Oliver seems to have first introduced the system to the public at Montreal in 1884.* Sir Oliver there showed experiments with magnesium smoke in glass globes fitted with points of wire connected to an electrical plate machine. When the current was turned on it is stated that the smoke and dust crystallized or solidified into filaments and streamers on the points of the wire.

The Cottrell system was tried at the Ann Arbor Town gas works,† but the trouble in keeping the electrodes insulated appears to have prevented a more general application of the system and, so far as the author has been able to ascertain, it has not been applied to producer gas.

The Steere Engineering Company of Detroit have also used static electricity. In their case the current employed was alternating.

Although these systems have been highly successful in connection with the precipitation of dust in the smelting and cement industries there appears to be difficulty when applied to gas cleaning in keeping the electrodes free from tar deposit.

A recent application to Sir Oliver Lodge drew from the Lodge Fume Company the statement that they are working on the matter in this country, but it is too early yet to say anything definite about it.

Circulating pumps and pipes.—Owing to the comparatively small quantity of water circulated round the washers, 200 gallons per minute, the pumps are small and light. It was found that small pieces of wood, and small stones mixed with tar and dust, collected in the casings which, in larger pumps, would have been carried through. Pumps for this purpose should have outside bearings and a flexible coupling to the motor; the glands should be ample in size for flexible packing and easily adjustable.

* *Electrician*, 27 Sept., 1884.
† *American Gas Light Journal*, 21 Sept., 1914.

The delivery and suction pipes should be arranged as short as possible, since the efficiency of the cleaning plant depends entirely on them and may be greatly reduced by a deposit of tar.

Cast-iron pumps were used for circulating the sulphate liquor on account of the difficulty in obtaining bronze. After running about six months these began to give trouble due to corrosion by the acid, particularly round the chaplets. Attempts were made to repair them, but after the Armistice it was decided to replace them with bronze pumps.

Gas mains.—These are fitted with dust outlets and poke-holes which enable the attendant to keep the pipes clear while the plant is in operation. This is not difficult when running continuously. It was found, however, that due to the week-end stoppage there was a tendency for the inlet to No. 1 washer to get blocked, and also the bottom of the downcomer from No. 1 washer. Additional poke-holes were provided at the inlet and a water-luted outlet was fitted to the downcomer.

In the second plant the bottom of the downcomer has an open end dipping into a lute, which prevents any accumulation of dust in the main at this point.

It is not necessary to clean out the gas mains except at the usual holiday stops during the year, viz. Easter, August, and Christmas, when all the extra cleaning necessary can be effected.

Temperature and pressures.—Fig. 4 shows the air and gas temperatures and pressures at important points from the blower through the producers to the gas leaving the works.

It will be noticed that as far as possible the gas pressures, both positive and negative, are kept low. The greatest variation is before and after the centrifugal cleaners. This cannot be avoided if the gas is to be delivered at a reasonable pressure to the works.

In the "Mond" plants it is customary to keep the pressures always above atmosphere. The disadvantage is the increased pressure at the producer and washers which leads to loss of gas due to leakage, also some discomfort for the men working the plant, particularly those who have to poke and keep the producer fires in good order.

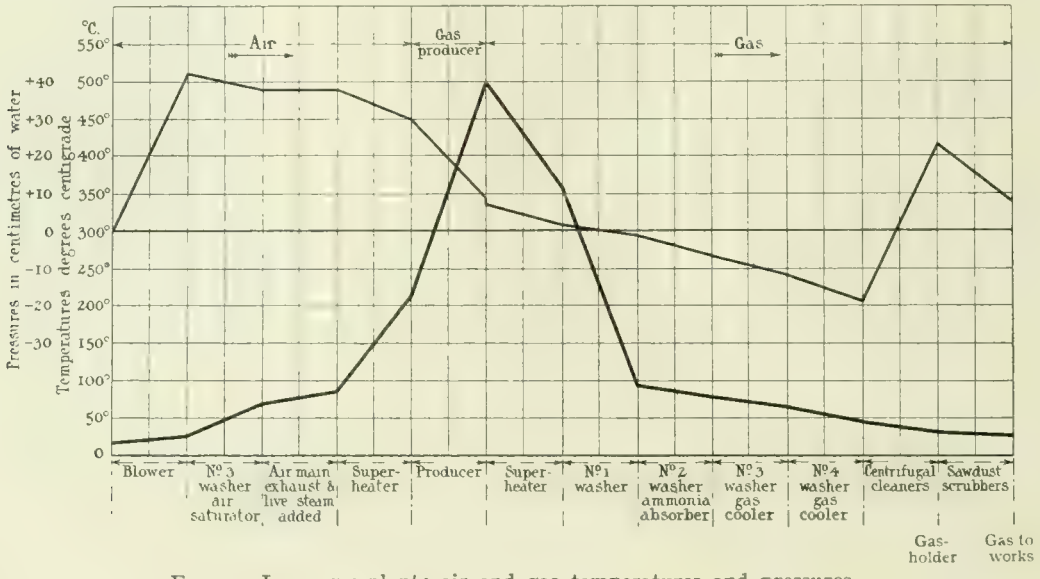


FIG. 4.—Lymn gas plant: air and gas temperatures and pressures.

General Remarks.

After all that has been heard recently concerning the efficiency of electric power stations it is interesting to compare the figures with those of Messrs. Hoffmann's plant which, for the six months period quoted above (Table 2), consumed 1·51 lb. of coal per unit and show a thermal efficiency of 19·9 per cent on the units delivered to the feeders.

Mr. David Wilson (Technical Adviser to the Controller of Coal Mines) gave figures for the year ending March 1918 at a Meeting of the Junior Institution of Engineers, 27th February, 1919.

	Output in Units		Coal per Unit (lb.)	Thermal Efficiency (per cent)
A	200,000,000	Stations in	2·53	10·88
B	40,000,000	the South of	2·32	13·05
C	22,000,000	England	2·49	11·95
D	200,000,000	Stations in	2·78	10·83
E	46,000,000	other parts of	2·40	12·35
F	28,000,000	the country	2·40	12·15

Subsequently published figures show that the eight stations in the Northumberland district in the year ending March 1919 generated 272·8 million units at an average consumption of 2·40 lb. of coal per unit generated. The best station in that district shows a coal consumption of 1·80 lb. per unit and a thermal efficiency of 18 per cent on the units generated.

The next district in order of merit is Durham with 13 stations generating 307·8 million units and an average consumption of 2·56 lb. of coal per unit, with a best

single station consumption of 2·2 lb. per unit and a thermal efficiency of 15·2 per cent.

Taking the whole of the 438 stations included in the returns, the units generated amounted to 4,623 millions with an average consumption of 3·46 lb. of coal per unit. The calorific value of the coal is not available but, assuming 11,000 therms per pound, the thermal efficiency would be 9 per cent.

The Detroit Edison Company's figures which, by the kindness of Mr. Alex Dow, the author had the pleasure of sending to the *Electrician* in June last,* show a coal consumption per unit delivered to the feeders and a thermal efficiency for the six months' periods from June 1916 to December 1918, varying from 1·44 lb. and 17·33 per cent. efficiency, to 1·63 lb. and 16·33 per cent efficiency.

When comparing the capital cost of this plant with other costs it is important to note that, while the four producers are of large size, the gas washing and recovery plant is made up of eight vessels, the total cost of which is much greater than it would be if the plant had been put down at one time as a 60-ton plant instead of as two 30-ton plants. Four vessels would then have sufficed which would not have been much heavier than four of the present vessels, and the consequent saving in pipe-work, foundations, and auxiliaries would have been very considerable.

As regards the use of gas engines, experience here as well as elsewhere has proved that they are reliable and, where gas is available—whether it is used for boiler firing or used direct in engines—will be determined largely by the size of the plant contemplated.

In the author's opinion the large-cylinder high-power gas engine will be developed in this country as it has been abroad. He is a firm believer in the quick-revolution steam engine up to a size, but it has its limitations which have been masked by the development of the turbine. If large gas-engine units are called for, as they surely will be, in greater numbers it does not appear likely that a multiplicity of small cylinders will answer the call. If a 3,000 h.p. unit can be safely developed on four cylinders, why use 24 cylinders? Meantime the gas turbine is not a commercial product.

For huge plants the steam turbine has no competitor, and the opportunities for combining such a plant complete with by-product recovery from fuel cannot be frequent, so it is more probable that in such plants direct coal-firing will be the rule, assisted, to a small extent, by surplus-gas-fired boilers as has been at present attempted.

Power is a necessity. Coal is a wasting asset and, while the engineer is anxious to convert coal into power, thermal efficiency must not outweigh all other considerations or be allowed to become a fetish.

The country needs power but it finds other products from coal necessary, and no amount of "cheap power" will take their place. Whether power (as electricity or gas), tar derivatives, or coke, is the by-product, can only be determined by consideration of the coal and the locality in which it is produced.

In dealing with fuel problems the first question to settle is, which is to be the product and which the by-products? Coke, gas, oil, ammonia, etc., present a large variety of alternatives for choice. The price and quality of the fuel, the cost of the plant, the cost of operating, and the possibility of disposing of the by-products at remunerative rates are all factors in arriving at the cost of the product. A comprehensive view of the situation is necessary.

We have only two minerals to export, coal and China clay, and we must make the most of them, exporting only the best at the best prices. The position of the industrial centres of manufacture has always been settled by the position of the potential power supply, in our case by our coalfields, and it seems at any rate a debatable question whether the country can be reconstructed on such a plan that natural advantages are of small account.

It is absolutely certain that low-grade fuel must be better utilized in the future than in the past. This should be used locally to save the cost of carriage. Any attempts to use such fuel have generally been abandoned in favour of high-grade fuel, whether for boiler-firing or for producer-gas plants. It is said to have been done for economy. Whether the altered conditions under which we shall have to carry on in the future will permit it is an open question; the factors which have to be considered in economy are rapidly changing in values.

For burning low-grade fuel an arrangement of a grate external to the boiler would be better than a grate directly under the boiler, as the grate need not be so restricted, and the next step is a producer grate. Siemens developed the circular producer for furnace work 40 years ago on much the same lines.

Calculations have been made showing the loss in producer gas firing of boilers, with and without by-product recovery, as compared with direct coal-firing, but these questions are not always settled by calculation. There are many variables and unknown quantities.

Both the gasification and carbonization of coal have been much discussed in connection with the fuel-economy campaign.

It is not all coal that will coke, nor is there an unlimited demand for coke. If there was such a demand the fact that coke is twice as bulky as the coal from which it is made would severely handicap its transport, which points to its being used locally. It must be admitted that there is no more likelihood of all coal being gasified than of it all being coked, but there is every probability of much more coal undergoing one or other of these processes than at present.

Low-temperature carbonization has no special therapeutic effect, and although in some quarters much is expected of it the industry still has to be established on a sound commercial basis. The semi-coke offers a pleasanter fuel for domestic hearths as an alternative to gas-coke, but it is not likely to displace furnace or foundry coke. Low-temperature carbonization will not make good semi-coke out of rubbish, any more than a high-temperature process will make good coke of it, and it remains either to wash all the dirt possible out of low-grade fuel or to burn it with a high-ash content.

To wash coal costs money and is only in part effective, while to burn rubbish calls for more labour in transport

* *Electrician* 1919, vol. 82, p. 702.

and handling, larger grates, and more heat is thrown away in the ash. The same considerations apply, no matter whether the burning is done in a producer or in a steam boiler.

To what extent sulphate of ammonia recovery from fuel will pay will depend not only on the nitrogen content of the fuel and its price, and the cost of recovery including capital charges, but also on the selling price of the sulphate, and this may be greatly affected by some of the processes of nitrogen fixation which have been so largely developed during the war. This last consideration is likely to have an important bearing on the adoption of an ammonia-recovery process from coal.

Again, we have an at present only partly explored field in the application of pulverized fuel. The high boiler efficiency, due to the possible close regulation of air, is attractive but is not assured, and if obtained may be too dearly bought when the cost of pulverizing and the trouble from dust and clinker is emphasized, as it is in the case of fuel with a high ash content.

A most disturbing element at the present time is the shortened week with only one operating shift. This is perhaps not the place to discuss its effect on the country, but we are certainly justified in stating here that load factor is the important element in cheap power, and a high load factor is impossible with a short working week and only one shift worked in the 24 hours. Such operating cuts at the root of economical power stations, and even if we supply over large areas this will not give a diversity factor to make up for the short working hours of the consumers. If manufacturing calls for cheap power it must remember that a low price depends on long hours of operating and a high load factor.

In conclusion the author desires to put on record his indebtedness to the managing directors of the Hoffmann Manufacturing Company for permission to publish these particulars of their plant, also to their staff and his own, and to Mr. A. H. Lymn, for their ready assistance rendered in the matter.

(The discussion on this paper will be found on page 437.)

THE PRODUCTION OF POWER FROM BLAST-FURNACE GAS.

By S. H. Fowles, Associate Member.

(*Paper first received 23 October, 1919, and in final form 1 June, 1920. Read before* The Institution 11 *and* 18 *March, before the* Tees-side Sub-centre, 8 *March, before the* North-Western Centre, 9 *March, before the* North-Eastern Centre, 22 *March, and before the* South Midland Centre, 31 *March,* 1920.)

Sir Charles A. Parsons mentioned in his presidential address to the British Association at Bournemouth in 1919, that the latest estimate of our total water power in the British Isles is only 1½ million horse-power, and that England possesses only 1 per cent of the water power and only 2½ per cent of the total coal in the world.

In view of this fact and that we as a nation have to effect a considerable saving in our fuel consumption, we must first of all look to our efficiency. In many cases this is very low and wasteful. It is for us to look for better methods of using our wasted heat units, and thus make the best use of what we have, before attempting to harness any new powers.

One instance of great wastage is in the form of blast-furnace gas, which escapes from the furnaces during the making of pig iron, and it is to give some rough outline of the better way in which this gas can be, and is being used, that this paper is written. The author hopes that it will prove of some little value to all engineers.

The amount of energy which is at present being wasted or used at about 10 per cent efficiency from the blast furnaces of this country is in the neighbourhood of 1 million horse-power. This is a matter that should be seriously taken up in connection with the greater power scheme, and should serve a very good purpose in the cheapening of electrical energy.

Table 7 in the Appendix (page 436) shows the savings that can be effected where the gas is cleaned and used efficiently; thus, for the same quantity of gas an additional 10 thousand horse-power can be produced, and about 5 to 6 thousand horse-power saved on coal, making a net saving of about 16 thousand horse-power from three blast furnaces.

The gas is a by-product and has been treated in the past as of very little value, being therefore either wasted or used very inefficiently. The furnaces are self-contained, with a large number of boilers for steam-raising to supply the blast engines for the furnace blowing. This blast in turn passes from the engine-driven blowers through the hot stoves to the furnaces. The hot stoves and boilers usually consumed the whole of the gas made, in addition to a very large amount of coal for the boilers.

The gas was used in its crude state, with the exception of the small amount of dust taken out by the dust catchers, which amounted to about 20 per cent of the initial dust in the gas, the dust quantities at this point being in the neighbourhood of 8 grammes per cubic metre. This considerably choked up the boiler tubes and flues, and caused great loss in laying off the boilers for cleaning, which was a very frequent occurrence when it is seen that the boilers consumed about 1 million cubic feet of gas per hour.

In addition to the dust, the moisture had to be dealt with, and this considerably lowered the temperature of the fire box, thus causing the excessive use of coal with very inefficiently burnt gas. Many of the boilers on this class of work are in the open air and have no shelter; the settings are very often so porous that it is far from economical to use even clean gas on them, but during the transition stage this has to be done. The use of gas for boiler-firing is proving a very bad policy, since in comparison with large gas engines only about 30 per cent of the engine efficiency is maintained on the boilers of modern design on clean gas.

Old and New Methods of Utilization of Waste Heat.

The gas which is produced from the coke, limestone and ore during smelting was originally blown entirely to the atmosphere as waste. After some years of this the iron smelters discovered that the gas was useful and so they employed it in its crude state under the steam-raising boilers, these supplying steam for the furnace blowing engines. A slight economy was realized on the coal used. This went on for a number of years, the blast being taken direct from the blowers to the furnaces at about atmospheric temperature. Later it was thought that to heat the blast before entering the furnace would be a still further economy and increase the production of the furnaces, and large vertical stoves were therefore designed to heat the blast.

Operation.—First the crude gas was turned into the stoves and was kept burning until the stove's firebrick lining was raised to 700–800° C.; then the gas was cut off and the blast from the blowers turned through the heated stoves on its way to the furnaces.

Considerable saving was effected in the coke used in the furnaces by this step. From that time up to about 1913 this was common practice in this country, about 40 per cent of the gas being used for the hot stoves and 60 per cent for boiler-firing; in addition, about 80 tons of good coal per week were used for the boilers on one furnace.

The flues were always in a very clogged state and the efficiency of the boilers was very low owing to the dust in the gas coating the boiler tubes and becoming a very good heat insulator, and to the moisture in the gas having to be raised to fire-box temperature.

It will be seen from the foregoing that all the gas made was easily consumed by the furnace auxiliaries themselves.

The following are approximate figures for one furnace on the old method:—

Gas made per hour	1 million cub. ft.
Gas used on hot stoves	0·4 million cub. ft.
Gas used on boilers	0·6 ,,
Total gas used per furnace.. ..	1·0 ,,

Coal used per furnace per hour = 0·5 ton.

The furnace blowing averaged about 600 h.p.

So that 600 h.p.-hours took 0·5 ton of coal + 600,000 cub. ft. of gas at 100 therms per cub. ft

Now therms in coal at, say, 13,000 per lb.	=14,560,000
,, in gas at, say, 100 per cub. ft.	=60,000,000
Total therms	74,560,000

This number of therms used as gas in our present-day gas engines would develop about 6,500 horse-power, which shows the old method of using crude gas and coal to have an efficiency of about 10 per cent when compared on a horse-power basis with our present-day gas-driven plant.

The following are approximate figures for one furnace on the new method :—

Gas made per hour	1 million cub. ft.
Gas used on hot stoves	0·4 million cub. ft.
Gas used on boilers	Nil
Gas used per furnace on blowers ..	0·15 ,,
Total gas used per furnace ..	0·55 ,,

Coal taken per furnace per hour for hoists = 0·2 ton.

Furnace blowing = 800 h.p. owing to increased production due to higher stove temperature on clean dry gas.

So that 800 h.p.-hours take 0·2 ton of coal + 150,000 cub. ft. of gas at 100 therms per cub. ft.

Now therms in coal at 13,000 therms per lb.	= 5,824,000
,, in gas at 100 therms per cub. ft.	=15,000,000
Total therms	20,824,000

Therefore each furnace produces 1 million cubic feet of gas per hour and only 0·55 of this is required for the furnace, leaving 0·45 million or 450,000 cubic feet of gas available per furnace for other purposes, and this at 150 cubic feet per kilowatt-hour is equal to about 3,000 units of electricity per furnace per hour.

Now with 50 furnaces the aggregate would equal 150,000 units saved per hour and 1,030,510,000 per annum; this with the boiler saving represents an economy of about 400,000 tons of coal per annum. This shows that the electrical energy which can be saved annually by generating from blast-furnace gas is almost equal to the total number of units sold during 1911–1912 by all the 303 electricity works of the United Kingdom, as mentioned in Table 7.

Table 7 (page 436) shows the difference in coal and gas consumed, and the work done under crude and clean gas conditions respectively, and it will be realized that the saving is enormous. A great deal depends on the selection of a cleaning plant for this purpose, and while it is not intended to compare the merits or demerits of other plants, yet a great deal can be said for the Halberg-Beth type. So far as this plant is concerned it is a dry gas-cleaning plant, but water was used in direct contact with the gas in the pre-coolers, and this has now been eliminated.

Nevertheless, this plant after some alterations has given excellent results. It has considerable advantages, which will be seen later, the following being a few of them :—

The bulk of the potash is recovered in its original state.

The water is taken out of the gas to a large extent, this being greatly in favour for gas-engine running, and also for boiler firing, but especially for engine use.

The dust contents are very low, the average being 0·002 gramme per cubic metre.

The plant can be worked for long periods up to 30 per cent overload if required.

The moisture can be removed or allowed to remain at will.

The total water contents average about 15 grammes per cubic metre. This is very low, and of great advantage in gas-engine running. Many alterations have been made in the operation of the plant to obtain these conditions, the original German plant being designed for boiler-firing only where gas of a higher dust and moisture content was tolerated, but was eventually arranged to clean gas of sufficient cleanliness and dryness for engine consumption.

The above figures can hardly be surpassed to-day on any plant when the dust and moisture are taken into consideration jointly and the power consumption per volume of gas cleaned.

The plant consists of three filter units of 11 double compartments each, with a total nominal capacity of 3·3 million cubic feet of gas per hour, and is provided with fans of a nominal total capacity of 4 million cubic feet of gas per hour, the gas quantities being taken at 0° C. and 30 inches barometer.

Other cleaning plants, so far as is generally known, are not in a position to guarantee such results of low dust and moisture contents which is common to engines, boilers and stoves, so that in case of a temporary shortage of crude gas the valves to stoves and boilers can be closed and the engines kept running continuously.

Another great advantage of this plant is the fact that, with no complete water passages or seals for the gas to pass for cleaning, in the event of a stoppage occurring on all the fan motors in the cleaning plant the engines will continue on load as usual, and will draw the gas through the plant just as clean as when supplied by the fan. This has been done for a period of an hour at a stretch and is a great advantage in the event of a shut-down. In a case of this sort, the boilers and stoves are kept supplied by the crude gas pressure building up, and it can be allowed to push through the bags about one-third of the gas required to the boilers and stoves, and so everything is kept moving with some gas, the principal portion being the engines.

The fans are of the double-inlet type, and are capable of delivering a pressure of air equal to 12 inches (water gauge). They have been run continuously for two years and have not required cleaning or any repairs. This will show the low quantities of water and dust after cleaning.

The guaranteed power consumption is as follows, and is not to exceed these figures by more than 10 per cent :—

150 h.p. when dealing with 2·75 million cub. ft. of gas per hour at a delivery pressure of 2 in. (water gauge).
180 h.p. when dealing with 2·75 million cub. ft. of gas per hour at a delivery pressure of 4 in. (water gauge).
180 h.p. when dealing with 3·0 million cub. ft. of gas per hour at a delivery pressure of 2 in. (water gauge).
210 h.p. when dealing with 3·0 million cub. ft. of gas per hour at a delivery pressure of 4 in. (water gauge).

The motors are direct-current, shunt-wound, interpole 500-volts 160-b.h.p. machines and run at 900 r.p.m., and are of variable speed up to 1,170 r.p.m.

The actual consumption is as follows :—

95 h.p. when dealing with 1·35 million cub. ft. of gas per hour at a delivery pressure of $4\frac{1}{2}$ in. (water gauge).

These figures show a slight reduction on the guaranteed figures equal to about 3 per cent in favour of the guarantee. This becomes a considerable item in the year, since with two fans running, and taking a total of 1,448,200 units per annum, the saving equals 44,000 units. This saving has been brought about absolutely by dry and clean gas working, in order to keep the fan dealing with a gas as high in density and as low in temperature and moisture as possible. The result is that after two years' hard working the fans are more efficient than the maker's guarantee figures.

Immediately above the main fans, and on the suction side, a main is taken out to supply the counterblast fan, which delivers a quantity of cleaned gas continuously through a reheater to the clean side of the bags in the compartments only that are open for cleaning and shaking. During this operation the shaking gear operates a double-way valve, thus cutting off the main fan suction from that particular compartment and opening the path for the clean counterblast gas, which is at a pressure of a few inches (water gauge) above the pressure at the pre-heater bottom. The counterblast flows through the bags, takes the dust from the inside, and passes on with the gas to be cleaned.

The arrangement is shown in Fig. 1, from which the simplicity of the plant will be realized.

The plants work continuously and have a very low upkeep and operation cost, as will be seen from the tables given in the Appendix.

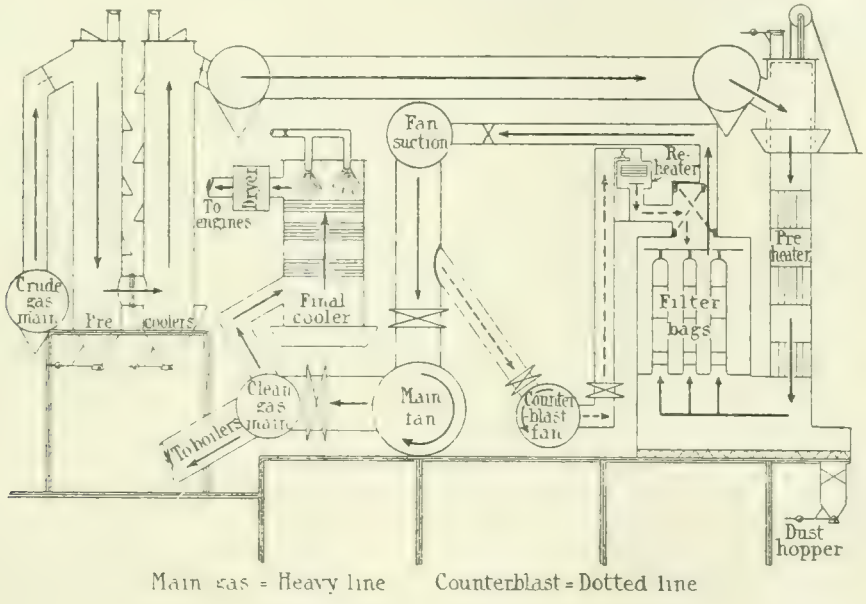


FIG. 1.—Diagram of Halberg-Beth gas-cleaning plant.

The total area of filtering medium is 16,632 sq. ft., and 5 per cent of this is automatically shut off every 10 minutes for shaking and cleaning. The dust which is recovered from the cleaning of the gas is about 50 tons per week, and is equal in potassium chloride to about 30 per cent.

The general operation of the plant is as follows :—

The crude gas is first cooled in the pre-coolers and lowered in temperature from about 200° to 80° C., a large amount of dust and moisture being deposited. It is then heated up about 10 or 15 degrees C. to allow of the gas passing through the plant with its moisture contents superheated, and not to be influenced by the surrounding atmosphere, which is liable to deposit moisture and so clog up the filter bags. The gas then passes the filter bags where it is cleaned and its dust removed, afterwards passing to the main fans, and is finally delivered by them to the respective places for consumption.

The engines for generation comprise seven sets of 12-cylinder tandem vertical 1,500 h.p., direct-coupled to 1,000-kw. three-phase alternators running at 200 r.p.m. and are run in parallel with a public electric supply at 5,500 volts.

In order to get good firing, the sparking-plug points are adjusted to about 15/1000ths of an inch, and are of the motor-car large type supplied from a low-tension magneto and induction coil, and very little trouble is experienced by dirt or moisture owing to the gas being dry and clean when leaving the gas plant. The throttles for air and gas are arranged on a common spindle, and the air throttles require more cleaning than the gas throttles, which shows that the gas is cleaner than the atmosphere. The machines run very steadily and synchronizing is quite as easy as on a steam-driven set.

The blowing engines of four sets are of the horizontal type with two double-acting gas cylinders and one double-

acting blowing cylinder. They run at 85 r.p.m., are of 1,650 h.p. and can deliver 36,000 cubic feet of free air per minute up to a pressure of 11 lb. per square inch, or a decreased volume up to 15 lb. per square inch. These engines supply the blast for the furnaces, and have been in operation for 1½ years very successfully. The ignition is on the low-tension drawn-out plug, operated with a solenoid in series, so that directly the arc breaks, the plunger is spring-returned ready for the revolving contact passing its brushes again on the lay shaft.

The gas is quite free from tar, and pistons drawn after six months' running were found to be as clean as when first installed.

A great deal of attention has been given to the operation and maintenance of the cleaning plant, as it was very early decided that we must have clean gas. This being as clean as town gas and of low calorific value but very constant, makes gas engines as reliable as steam engines.

During the early periods of operation it was decided to overhaul the engines twice per annum, but after several inspections it was found that we were able to run for twelve months before overhauling. The usual repairs common to all engines are taken in hand at the week-ends.

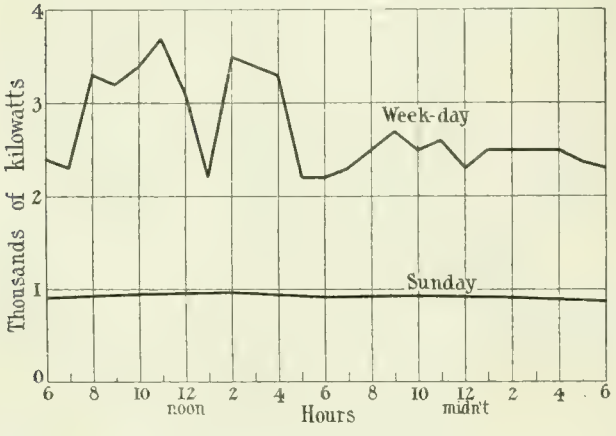


FIG. 2.—Typical day load.

Several tables are given in the Appendix to show the various constituents of the gas, the constant value, the gas and oil used in various parts of the works, the number of units generated, and the pressures and temperatures maintained at various positions in the cleaning plant and engine rooms.

The exhaust gases have been tested and the following is the average of the general tests taken :—

Number of Engines Working	Temperature	N	CO_2	CO	O
	°C.	per cent	per cent	per cent	per cent
4	337	78	14·0	0·26	8·3

Table 1 shows the constituents of the gas, the therms per cubic foot, the dust and moisture contained in the clean gas, and the quantity and contents of the dust. Table 2 sets out the results in the engine room on the generating engines. Table 3 shows the quantities used at the blowing engines. Table 4 deals with the gas cleaning plant, while Table 5 deals with the gas temperatures and pressures in the gas plant and the engine room respectively.

Curves of the various loads are given in Figs. 2 and 3, and show the usual conditions in iron and steel works. A great deal depends on these conditions as to how the electrical world can make great use of the intervals should all the blast furnaces of this country become interconnected with the greater scheme of power supply.

In the daily load curve (Fig. 2), it will be seen that from 5 p.m. to 7.30 a.m. about 3,000 kw. of plant is idle. The whole of the gas is wasted during this period, and could be very usefully employed to supply power to a network

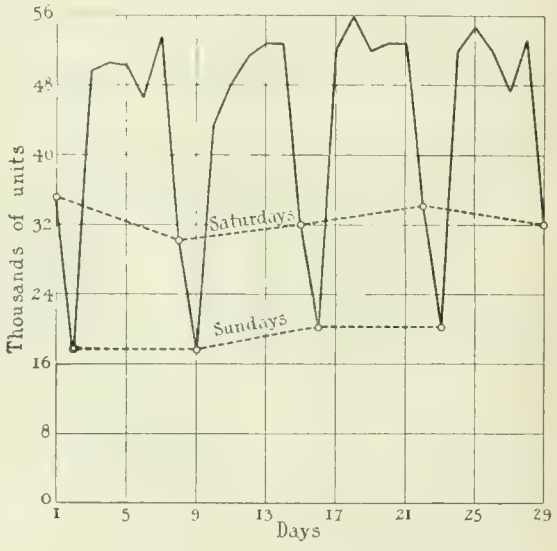


FIG. 3.—Monthly curve of units generated.

through converting plant, thus allowing several medium-sized towns to take their supply from such a source and reduce considerably their coal, stores, and probably their wages costs during this period.

A still greater loss is shown on the Sunday curve from Saturday noon to 7.30 a.m. on Monday, when 4,000 kw of plant is idle and could deal with the week-end load of several medium-sized towns, thus allowing the boilers in use and the staff to be considerably reduced and effecting a great saving of fuel and wages. It would also allow of a good many repairs being done, and so decrease the stand-by plant in many cases.

This matter should be considered seriously, as already we are making use of our water supplies which are not so constant as this supply. We have now some 20 places in this country where blast furnaces are working, and these are to be increased during the next few years. Many of these places cannot consume the whole of their gas produced, and with the adoption of cleaning plants such as have been mentioned, and the use of large gas

engines, the time has arrived when still more and more gas will be available from two sources, viz.

(1) From the coke ovens, and
(2) From the coke used in the blast furnace.

The quantity of gas wasted, although small compared with the requirements of our power stations, is nevertheless a large item when taken collectively in the balance sheet.

The coke-oven gas mentioned above is richer in value than blast-furnace gas and is not quite such an easy gas to use, but during the last three years a very ingenious valve has been adopted for mixing some of the exhaust-cooled gas from the engines with the coke-oven gas, thus avoiding the trouble of pre-ignition.

The whole of this subject should have a thorough investigation, with the ultimate view of connecting all blast-furnace supplies to the greater scheme of national power supply.

The hot stoves are kept fully supplied with clean gas, and consume about one million cubic feet of gas per hour.

The boilers are fully supplied with clean gas, and consume about 0·6 million cubic feet of clean gas per hour.

The whole of the furnace blowing is effected by large gas-driven engines.

The whole of the power for the blast furnaces, steel works' rolling mills, and the shipyard, which totals about 5,000 kw., is obtained from the gas that was originally consumed for the furnace auxiliaries when crude gas was used. In addition to the greater output, we recover the large amount of potash previously mentioned and shown in the tables, and a large quantity of gas is still being wasted and could be used for electricity generation as shown in the balance sheet.

Sufficient has been said, I think, to prove the great use that can be made of blast-furnace gas in the greater scheme of power production. The base has now been formed, and it is to be hoped that the highest efficiency will be obtained by all who are connected with this valuable heat-raising source.

TABLE 1.

	N	CO_2	CO	H	Therms per cub. ft.	Grammes per cub. metre in Clean Gas		Chlorides as KCL in Recovered Dust
						Dust	Moisture	
Constituents of gas	per cent 60·8	per cent 7·50	per cent 28·1	per cent 2·52	68·5	0·0023	15·0	per cent 30·637

TABLE 2.

Generating section—results per week.

Units generated	3[illegible],350
Gas used	59,452,500 cub. ft.
Oil used	34 galls.
Grease used	30 lb.
Waste used	05 lb.

TABLE 3.

Blowing section—results per week.

Gas used	49,247,000 cub. ft.
Oil used	95 galls. ; i.e. 0·284 gall. per engine hour
Grease used	35 lb.
Waste used	56 lb.

TABLE 4.

Gas plant—results per week.

Gas cleaned	468,216,000 cub. ft., or 2,787,000 cub. ft. per hour
Bags changed	8
Oil used	8 galls.
Grease used	10 lb.
Waste used	12 lb.

TABLE 5.

Gas Temperatures	Atmosphere, 16° C.	Crude Gas, 250° C.	After Coolers, [illegible] C.	After Preheaters, 82° C.	Stoves and Boilers, 73° C.	Engines, 23° C.	Counterblast, 107° C.
Pressures, inches (water)	--	−4·2	−0·2	−3·9	−4·8	−5·7	−3·8

SUMMARY.

It is shown that with the waste crude gas from three furnaces the following work is done :—

APPENDIX.

Table 6. Comparison of Old and New Methods.

	Old Method	New Method
Gas made per furnace per hour	1,000,000 c. ft.	1,000,000 c. ft.
Furnace rate of working	Normal	10 % increase
Coke per ton of pig iron made	23 cwt.	21 cwt.
Units of electricity generated per furnace per annum	Nil	6,870,000
Potash saved per annum	Nil	£6,000
Flue-cleaning costs per annum	£1,000	Nil
Coal used per furnace per hour	0·5 ton	0·2 ton
Horse-power used per furnace per hour	600	800
Therms used per furnace per hour	74,560,000	20,824,000
Gas used per furnace per hour	1,000,000 c. ft.	550,000 c. ft.

Table 7.

Showing the changes effected by cleaning and using blast-furnace gas efficiently. The comparisons are taken over a working year.

Losses Incurred on Old Method.

	£
Coal used on boilers	19,350
Extra coke used on furnace	13,650
Cost of electrical energy bought	88,540
Flue cleaning	1,000
Potash lost	6,000
Total	£128,540

Saving by New Method compared with Old.

	£
Capital expenditure	200,000
Annual repayment	30,000
Coal saved per annum	18,000
Coke saved per annum	13,650
Potash recovery	6,000
Saved on units generated	70,834
Value of extra units generated	28,340
Saved on flue cleaning	1,000
Total	£137,824

Summation Balance

	Dr. £	Cr. £
Capital repayment and interest	30,000	
Coal saved		19,350
Coke saved		13,650
Saved on electrical energy		88,540
Saved on flue cleaning		1,000
Value of potash recovery		6,000
Value of extra units generated		35,425
Total wages paid per annum	16,800	
Wages on old boilers	3,900	
Total oil costs	2,912	
Total stores	1,000	
	£54,612	£163,965

Units generated per annum		20,610,200
Saving, gross	£163,965	
Less capital and wages	£54,612	
Net saving	£109,353	

Table 8.

Comparison of 303 electricity works and the estimated waste gases of Great Britain's 50 blast-furnace plants :—

303 Electricity Works	1911–12	50 Blast Furnaces
Capital expenditure of total new plant	£93,788,732	£10,000,000
Total revenue from all sources	£8,675,900	£8,195,750
Working expenses	£4,086,704	£2,730,600
Gross profit	£1,589,196	—
Net profit	£2,880,939	£5,465,150
No. of units sold	1,127,490,742	1,030,510,000
Working costs per unit	0·87d.	0·3d.
Plant capacity in kw.	961,520	565,000
Capital per kw. of plant capacity	£35	£17·7

Discussion on the Papers by Mr. Patchell and Mr. Fowles before The Institution, 11 March, 1920.

Mr. C. P. Taylor: I propose to confine my remarks to Mr. Patchell's paper. I have had an opportunity of seeing the plant which he has described, and I think it is in every way admirable. From considerable personal experience I think the author could not have done better as regards the engines, but I believe they are capable of working at even a slightly higher efficiency than he has stated. Regarding the producer plant, stress is rightly laid on the importance of the steam supply, which is really a crucial factor. I do not understand one or two statements made in the paper in that connection. On page 423 the author states that: "By using these boilers and burning tar 75 per cent of the 25 per cent of the coal required for the gas plant is provided, and the actual coal required for gas-plant steam is reduced to 6·25 per cent of the coal gasified." On the top of page 424, however, he says: "As will be seen from the table more steam is raised by the exhaust boilers than is required to make gas for the engines." I do not understand that. On turning to Table 2 one sees in the third column that it says: "Coal, if 25 per cent is required to provide steam, =347·5 tons"; and later on it states that the amount of coal saved by the exhaust boiler is 379 tons, a little more. It appears to me that the position is this: one can get from the exhaust-heat boiler rather more steam than is required to make the gas for the power alone. That means to say that one is using only the 1·7 lb. of coal per kilowatt-hour in the producers, and that steam is not required from any extraneous source. In reducing the net consumption, as the author does, from 1·7 to 1·51 lb., that reduction is made, apparently, by an excess of 30 tons expressed as coal, which is really in the form of steam from the exhaust-heat boiler, and also by an equivalent of 114 tons obtained from the tar. I think the author is perfectly justified, considering the conditions under which he runs his plant, in stating that the coal for power purposes is only 1·51 lb. per unit; but in these cases where heat and power are being supplied at the same place, the author quite rightly mentions that every case must be considered on its merits; one cannot have a general case. For those of us who are more concerned with supplying power only, we must not take that 1·51 lb., because if power only were being supplied we could not do it. The excess steam produced by the exhaust boilers cannot, I think, be considered to be more than a working margin, and as regards the tar one can get rid of it in other ways. Looking at it, therefore, purely from the power point of view, the coal consumption should be put as 1·7 lb. per kilowatt-hour and there should be a credit for the sale of tar. This brings one to the cost table given at the bottom of page 426. I think it would be very valuable if the author would divide that table up a little more. He appears to have given credit for the sulphate on the value of the coal. That, of course, is perfectly justifiable, but it would be clearer, and I think more valuable from some points of view, if the author would give the gross cost of the coal and show the saving made by the sulphate. I think that is important from this point of view, that one of the many questions one has to consider in a matter of this sort is whether it pays to recover the sulphate or not. I therefore think it would be desirable to have a separate item showing what is made out of the sulphate. If one takes the figure that I assume, 1·7 lb. of coal, which is the total amount put in the producer at the average price of 28s 11d., the fuel, instead of being 0·166d., is 0·268d. The difference is very marked, but one gets it back in some other way. If those figures could be given it would add to the value of the paper very considerably. I agree with the author that the lubrication is too high, but if he has now halved it I think he has done very well. The renewals and repairs are, I think, rather high considering that the plant is new. When the time comes for the gas-engine cylinders to be bored and new pistons fitted, and when some of the gas plant begins to wear out, the figure may become rather high compared with those which I have available. I should like now to refer to the efficiency of the producer plant. This is rather difficult to ascertain, but I have made an effort to do so. I have taken, at 75 per cent load factor, the gas consumption of the engine in therms at 14,750 per kilowatt-hour. I think that appears to be a fair figure. I have taken 3·6 per cent for the amount used for power in the plant, which gives 15,280 therms per unit produced for sale. If that be divided by the heat value of 1·7 lb. of coal, one gets a producer efficiency of 79·3 per cent. I think that is a justifiable way of arriving at it, although it is not a very direct method. The result is very good—I think it is too good. In that connection I should like to refer to two papers by Bone and Wheeler which were read some years ago before the Iron and Steel Institute. Tests were there made at various saturation temperatures between 60° C. and 80° C. Sulphate was not being produced. The net efficiency given is not simply the efficiency as between the total heat of the coal and the total heat of the gas, but the authors give information from which that figure can be got. I have worked it out, and I find that the thermal efficiency of the producers was 80 per cent with 60° C. saturation, and it fell to 76 per cent when the temperature rose to 80° C. As the saturation was increased the CO_2 in the gas, which is a very vital factor, went up from 5·25 to 13·25 per cent corresponding to the gradual drop in efficiency. At Chelmsford the CO_2 is given as 15·8 per cent, which is higher than any of Professor Bone's figures, and yet the efficiency is practically as good as the best efficiency which Professor Bone got at his lowest saturation. That does not seem to me to be quite right; perhaps it is because I have not made the calculation correctly. If the author, with his fuller knowledge of the details, would make a calculation of that nature it would be useful, because we should be able to compare the efficiency of the producer plant as a whole with other figures which have been published from time to time.

Dr. T. B. Morley: I want to deal solely with Mr. Fowles's paper, which ought, I think, to attract the very widest attention. The fact that we are wasting at the present time, in spite of the developments that have taken place in blast-furnace practice, gas which would, upon the original reckoning of Mr. Fowles, amount to a saving of 400,000 tons of coal per annum, and on his corrected figures to 3,000,000 tons of coal per annum, is vital. The first point to be considered is how that energy is to be used. Mr. Fowles has advocated its use in large gas engines, and I think he is right. He could have made out even a better case than he has done. The statement at the top of the first column on page 432, that the old method of using crude gas and coal had an efficiency of about 10 per cent compared on a horse-power basis with our present-day gas-driven plant, is not quite clear. I think he means, not 10 per cent thermal efficiency, but an efficiency which is only 10 per cent of that attainable with present-day plant. On looking into his figures one will find, so far as the efficiency of the plants is concerned, that he has got 74,560 therms required by the blowing plant, which is taking 600 h.p. If one works that out it corresponds to a thermal efficiency of about 2½ per cent, which is 10 per cent of the 25 per cent obtained by the gas engine. In the figures a little lower down he gives the gas used per furnace on blowers as 0·15 million cubic feet. That is not quite in accordance with the figures which I think can be readily obtained, and which in fact are given later on in the paper. Taking 10,000 therms per b.h.p.-hour, which is offered nowadays by any maker of large gas engines, the figure of 150,000 cubic feet will be reduced to about 80,000; and if one compares those figures with the figures on page 435 one will see that the author quotes the gas consumption for the blowers using 800 h.p. as 49 million cubic feet per week. That corresponds to about 100,000 cubic feet per hour per furnace, instead of the 150,000 mentioned on page 433. I should like to draw attention to two very striking reports which were presented to the Iron and Steel Institute last September. One was by the Fuel Economy Committee of the British Association, the report being presented by Professor Bone, Sir Robert Hadfield and Mr. Alfred Hutchinson. In that report very striking testimony is given to the advantages to be gained by the adoption of gas engines in ironworks. The second report, which was even more striking in that respect, was presented at the same meeting by Mr. Cosmo Johns and Mr. Lawrence Ennis, two members of the Commission which investigated the iron and steel industry in the occupied territories on the left bank of the Rhine, and they showed that very striking use had been made there of large gas engines in conjunction with steel-works, both for using blast-furnace gas and coke-oven gas. They pointed out that, even in comparison with the burning of gas under boilers and using the resulting steam in steam turbines, the gas engine had a distinct advantage. When one talks about gas engines one meets with criticism, and one of the frequent criticisms is the lack of reliability. Mr. Fowles's paper is, I think, a sufficient answer to that. He deals in the paper with two types of gas engine—the horizontal slow and the vertical high speed; and both of them, he says, gave no trouble on the score of reliability. I would say to those who may be inclined to raise objections, that blast-furnace gas is free from the source of most of the troubles which have previously annoyed gas engineers, namely tar. There is no tar in blast-furnace gas, and, coupled with the cleaning system described by Mr. Fowles, anyone can be assured, either by the maker or by the user, that there is no trouble to be anticipated on the score of unreliability. Coming now to somewhat debatable ground, the question may be asked: what is the proper type of gas engine to use? The two types which come into question are the low-speed horizontal, and the multi-cylinder, comparatively high-speed, vertical. It is undeniable that, in respect of capital outlay and space occupied, the advantage lies with the vertical engine, but in the opinion of a good many competent judges the advantage ends there, and is offset, in fact, by the increased simplicity and freedom from liability to breakdown of the large horizontal engine. I heard the opinion expressed a little while ago by an engineer who had charge of stations comprising both types of engines, that he would sooner keep ten of the large horizontal engines in order than one vertical engine, on account of the large number of bearings to be kept in alignment in the vertical type. The large horizontal engine has very heavy parts, but that is offset by their simplicity and accessibility. In this connection it is rather interesting to consider the relationship between the life of the engine and the rotational speed. We have, at one end of the scale of internal combustion engines, the aero engine running at a speed of 1,600 to 2,000 r.p.m. and having a working life measured in hours; and at the other end, the large horizontal gas engine at, say, 80 r.p.m. with a working life which we have not yet been able to determine, because we have not come to the end of its life yet—the engines have been used for only a limited period of years and are still running. On page 435 Mr. Fowles has given some very interesting figures with regard to operating costs, but it would increase the value of the paper if he could add some figures with regard to the maintenance costs. I do not think the large gas engine need shrink from any comparative investigation. In that connection also I think it is somewhat significant that in Germany which, up till the outbreak of the war, was pre-eminently the home of the large gas engine, the sole type referred to by the above-mentioned Commission was the large horizontal engine. Objections are sometimes raised to the large horizontal engine because it has water-cooled pistons. In the Galloway blowing engine to which Mr. Fowles has referred there is only one water connection to a moving part, namely to the crosshead between the front and rear pistons, and I think Mr. Fowles will bear me out in saying that in his experience of this engine the water supply to the pistons has given no cause whatever for anxiety. Messrs. Galloways do not cool the exhaust valves by connection to the moving valve; their experience is that, even up to the largest size, cooling of the valve itself can be safely dispensed with. They have very special means of cooling the valve seat and the exhaust-valve box. The size of the cylinder of the blowing engine shown on the screen was 45 inches diameter, and Messrs. Gallo-

ways are quite prepared to build cylinders up to 55 inches diameter on the same system. In regard to the difficulty of starting, the author will bear me out in saying that even the largest engines in the station referred to give him no trouble at all on that score. Mr. Patchell has already dealt with the question of gas in the atmosphere and the consequent corrosion film upon electrical contacts. That, again, in a properly kept station is not a factor which need be feared in the slightest degree. There is one other point I should like to mention with regard to the large gas engine for blowing, namely, so far as I know, the makers of all vertical engines rely upon mechanically-operated valves which lift at a fixed point in the stroke. In working with a blast furnace there are many occasions when one wants the air at less than the normal pressure. If one has an engine the valve of which lifts at a fixed point, one must still compress at the normal pressure and then waste some of the work done. The large engine in which I am interested has automatic valves and that drawback is entirely overcome.

Mr. W. B. Woodhouse: Mr. Patchell tells us that his problem was to supply not merely power but heat. Roughly, he was supplying half the gas for heating purposes and half for power purposes, and I do not gather from his paper that, if the problem had been merely to supply power, he would have put in a producer plant or gas engines. One has to consider that the producer plant, whatever case there may have been for it in the days of coal at 5s. a ton, is a very different problem to-day. One has commercially a thermal efficiency of 70 per cent; in other words 30 per cent of the heat is thrown away. There are, in addition, the capital charges of the plant, the maintenance and the labour—and the labour is fairly considerable and very hard work, particularly when one has the wrong sort of coal that Mr. Patchell has mentioned. All those charges have to be made up by the sale of the only by-product, sulphate of ammonia. Taking Mr. Patchell's figures of the net value of the sulphate, after paying for acid and preparation, as being something like 10s. per ton of coal put into the producer on the profit side, on the other side there is 30 per cent of the cost of the coal, which at 30s. a ton is 9s., so that out of the remaining 1s. one has to pay for all those other charges; that is to say, in my view at all events, to-day practically no case has been made out for the by-product producer raising gas for power purposes alone. Mr. Patchell's problem, however, was different. A point that one may consider is whether there are processes of coal distillation which are justifiable. That is a very big subject, on which a great many people are working, and one which seems hopeful of solution; but the plain producer, as I have said, is worse off to-day than it was when coal was cheap. Mr. Patchell has made one other interesting point very clear in his paper, namely the high initial consumption of a gas engine. In other words, if one is going to use a gas engine, one should, to use it efficiently, run it on a load of high load factor. I think it can be said of both steam turbines and gas engines that the total consumption follows the Willans law fairly closely; there is an initial consumption and an additional consumption proportional to the output. In a large steam-turbine station the initial consumption is something between 15 and 20 per cent. In the gas engine that Mr. Patchell describes, he shows that the initial gas consumption or heat consumption is 66 per cent. It obviously would not pay to run that on a 10 per cent load factor. To use this class of gas in gas burners is not very efficient, but it is quite possible to do so—and much more efficiently than has been done in the past.

I confess I am disappointed with Mr. Fowles's paper; the author should make it clear which are estimates and which are actual figures of production. The comparison on page 436 of electricity works and blast-furnace plants is fallacious. Apart from the error as to capital expenditure, he is dealing with the number of units sold and neglects distribution losses. The general impression that the paper gives me is that the author is unaware of what has been done in recent years by ironmasters in utilizing blast-furnace gas. The position is not at all as bad as he would lead us to believe. In practically all the large works, ironmasters, realizing the value of their gas, have concluded that the proper and economical thing to do is to concentrate a steel plant around the blast furnace and utilize as much of the heat as possible in that direction, and then if they have any surplus—and they should not have any surplus—sell it to any public supply system as electrical energy. There was published in the *Journal* some years ago a valuable summary of the position and an analysis of the figures by Mr. Marshall. The previous speaker has referred to other publications. The British Association Fuel Economy Committee went into the matter to some extent. The Coal Conservation Sub-committee presented a report on the subject, and I am quite sure that the ironmasters of this country are really making good use of their gas. It is not possible in every case to use all the gas all the time, because the question of storage comes in, and it is not commercial to store large quantities of blast-furnace gas. Also there is the question of load factor and the disposal of electrical energy. Where a public supply of electricity is available, co-operation as to the disposal of surplus and provision of a stand-by is widely adopted. As to potash recovery, that is not necessarily confined to a plant using gas engines. Again, I think ironmasters are quite well aware that if they are going to run gas engines they must clean the gas, and that can be done in other ways than by the particular plant described. There is a statement on the first page with which I should like to disagree, as to the use of gas for boiler-firing being a very bad policy. The author says: "In comparison with large gas engines only about 30 per cent of the engine efficiency is maintained on the boilers of modern design on clean gas." Of course one really wants figures. Some years ago I put up a small power station designed to use gas as boiler fuel, and to produce electrical energy by means of a steam turbine. It was a small turbine, and its efficiency ratio was low, only 50 per cent. The overall thermal efficiency of that station was most carefully tested under commercial working, and it was 14 per cent. Had the same plant been on a larger scale it would have been quite possible to get a turbine with an efficiency ratio of 70 per cent; in other words, my 14 per cent would have been increased to something like 20 per cent.

Discussion (continued) on the Papers by Mr. Patchell and Mr. Fowles before The Institution, 18 March, 1920.

Captain A. P. Pyne: I propose to confine my remarks more particularly to the paper by Mr. Fowles. I may point out, however, that the thermal efficiency quoted by Mr. Patchell can be considerably higher in large gas power stations, and, if I understand him rightly, he has compared results obtained from a small gas power station with those from a large turbo-generator station. This is somewhat unfair to the gas proposition, and I know of one or two producer-gas power stations where considerably better results are obtained than those indicated in Mr. Patchell's figures or in the remarks of Mr. Woodhouse. Mention has been made by both these members of the poor efficiency of the gas engine at light loads. This is no doubt the case, but more particularly with the four-cycle engine. Gas blowing engines for some blast furnaces, not all, have frequently to run for considerable periods at from half to three-quarter load, and for this purpose the two-cycle engine possesses advantages over the four-cycle, inasmuch as it is easier to control and more efficient than the former under these conditions. I do not know of any two-cycle engine made in this country that can approach in reliability the Ehrhardt & Sehmer four-cycle engine, but there is at least one two-cycle type of Continental manufacture which has been brought to such a pitch of reliability that no one need hesitate to adopt it up to say 1,650 h.p. in one cylinder. There is a further point in connection with the engines selected. I notice that they run at 195 r.p.m., which Mr. Patchell regards as a low speed, and which he states he prefers to the high-speed vertical engine. I think I am right in saying that the standard speed of the vertical Westinghouse engines and the vertical National engines is 200 r.p.m.—not very different—although the smaller National engines are sometimes run somewhat higher than this. My preference is certainly for the vertical engine for small installations, and from the data which I have had before me during the past five years, I think there is a considerable future for the gas-engine power station, from whatever source the gas is obtainable. Anyone interested in this subject should read Mr. Percy Allen's instructive article in the "Oil Power" number of *Cassier's Magazine*, which, although published in March 1913, is by no means out of date. Among other information, a complete schedule of capital expenditure and running costs is given for two large power stations of approximately equal size, running in parallel under similar conditions in the Saarbrueken neighbourhood, one generating with gas engines on coke-oven gas, and the other with coal-fired boilers and steam turbines. The capital outlay involved is less for the gas power station in this case, but no gas-cleaning plant has apparently been included. The cost per unit generated in the gas power station is considerably lower than that for the steam-turbine station, but that is with gas at 2d. per 1,000 cubic feet against coal at 11s. 6d. per ton. The heat utilization of the gas-engine plant was 22·5 per cent, as against only 12·0 per cent for the steam system. In the same article it is shown that a given quantity of gas producing 2,000 kilowatt-hours in a boiler and steam-turbine plant will produce about 2,500 kilowatt-hours in a gas-engine plant under average conditions. In making up one's mind as to the type of power station to adopt, one has to decide whether the additional capital expenditure usually associated with gas-engine plant will compensate for the lower output obtainable from the steam plant, and in this one must be guided by the nature of the load, the size of the power station, and the local conditions. We cannot apply one set of figures arbitrarily to all the different conditions that may arise. Mr. Patchell emphasizes the freedom from gas and the freshness of the atmosphere in the power station he describes. There is no reason whatsoever why the atmosphere in a properly constructed gas power station should not be perfectly fresh and even preferable to that in a steam station. It may perhaps be of interest to know that in a very large gas power station in Germany palms and ferns were growing, carpets were laid between the engines, and a canteen decorated with flowers in pots was provided on the switchboard gallery for the use of the staff off duty. I have never seen a power station in this country as clean or well kept, but there are others on the Continent that could compete with it.

I was particularly interested in Mr. Fowles's paper, having been closely associated with the plant described, in fact being largely responsible for the outlay of the power station, from the selection of the engines to the smallest details. I assume that the principal object of this paper is to emphasize the economies and advantages to be derived from the proper utilization of blast-furnace gas. The figures may err a little on the optimistic side, but the main contentions are absolutely correct. I do not propose, therefore, to criticize details, but to support the author's views by supplementary remarks which may be somewhat coloured by the discussion that has already taken place. I am afraid Mr. Woodhouse is very wide of the mark in assuming that any considerable portion of our blast-furnace gas is being utilized to anything like maximum advantage in this country. He is still more so in stating that there is no surplus gas available after the needs of the blast furnaces themselves and steelworks (if any) have been provided for. It is one thing to be alive to the value of a product, and quite another to utilize it properly when, to do so, many problems have to be solved and considerable capital outlay is involved. The fact remains that a considerable source of power has been largely wasted by us in the past, and we have had to rely on the Germans to show us how to utilize it efficiently. As an instance of the way in which the Germans are not only alive to, but utilize all sources of power, I may mention one district which I have passed through, lying partly in the occupied zone, and which is dotted over with small blast-furnace plants each consisting of a single furnace producing a special

iron, and each keeping a gas engine running from their surplus gas. These plants were connected by high-tension lines with a large town having a central station containing a turbo-generator for steadying purposes. I was told that the system, which supplied the town, worked without a hitch, and a demonstration of this was given by telephoning to an outlying blast furnace (two miles away), and in less than 10 minutes a gas-driven alternator had been started up and was running on the town load. I will quote two paragraphs from a paper read before the Canadian Institution of Chemical Engineers a good many years ago, which clearly indicates that a large quantity of surplus gas is available after satisfying the requirements of blast-furnace and steelworks plant. During the years from 1911 to 1914 I had exceptional opportunities for collecting data relative to this question. This data resulted from visits to a large number of steel-works on the Continent, some works having been visited three or four times, and was obtained by personal inspection, by examination of log sheets covering long periods, by inquiries from attendants and others, and from correspondence with power-station engineers in various countries, including several power stations in Russia, who replied very fully. The results were tabulated and every effort was made to avoid using doubtful information. The conclusions arrived at may be interesting, though time will only permit of my dealing with generalities. They are as follows :—The advantages to be derived from cleaning the gas were always considerable, and sometimes enormous, whether used for stoves, boilers or gas engines, and the cleaner the gas the better, especially for gas engines. When clean gas was used, a large surplus was available for purposes other than at the blast furnaces. (May I point out that in the case of the power station described by Mr. Fowles, the total power needs of a large steel-works, shipyard, engine works, boiler works and several other establishments are supplied, and a considerable surplus remains available.) The gas not required by the blast furnaces can be used for generating electricity, either by means of steam boilers and turbo-generators or directly in gas-engine-driven generators. Given the right plant, the gas-engine proposition was equally as reliable as the steam proposition. Steam plant is usually lower in first cost than the gas-engine plant, but having regard to the greater economy of the latter, its adoption was fully justified, provided suitable up-to-date plant was installed, this being an essential factor. Prior to 1914, no really up-to-date plant, such as was to be found in Germany, existed in this country. Either the engines, though new in some instances, were of a pattern insufficiently reliable and becoming obsolete on the Continent, or the gas-cleaning plant was entirely inadequate. In either case the result was manifest in undue repairs and general disappointment with the plant. With regard to reliability, I have a record of an engine having made a test run for 24 hours per day for 365 days without a breakdown or stoppage for cleaning or inspection. It probably was stopped for a few minutes occasionally for minor adjustments, but my information does not imply even this. Elaborate arrangements were made to cope with ignition troubles. It is unlikely that this performance could be approached in any gas power station in this country under their existing conditions, but there is no reason why it should not be if suitable plant to produce the required conditions were provided. No doubt Mr. Fowles can tell us something on this point. By suitable plant I mean gas engines, excellent as regards design, material and workmanship, such as can be found in the Ehrhardt and Sehmer and one or two other types. Gas-cleaning plant must be provided capable of cleaning the gas down to 0·002 gramme per cubic metre, such as the Halberg-Beth filter plant. Neither engines nor gas-cleaning plants have reached finality, and just prior to the war interesting developments were taking place, which will in all probability be resumed, such as the application of scavenging to four-stroke engines, resulting in considerably increased power per cylinder. This has been occasionally tried with indifferent results in this country so far, but has achieved a measure of success in Germany, and further developments in this direction may be expected. Exhaust gases may be used to provide the steam for the pre-heaters of the Halberg-Beth plant or for driving steam-turbo pumps for the scavenging plant. Other economies of a similar nature remain to be investigated. The reliability of the gas engine, apart from manufacture, depends mainly on the cleanliness of the gas, and so far the Halberg-Beth plant has come up to the requirements in this respect, but the cleanliness of the gas delivered by this plant, namely, 0·002 gramme per cubic metre, is, as indicated by Mr. Fowles, cleaner than the surrounding air ; and the time has now come to clean the air as well and so obtain still better results from the gas engines. I think Mr. Fowles mentioned that the air valves were much dirtier than the gas valves of the engines in his charge. With regard to gas-cleaning plant, much scope exists for improvement. The Halberg-Beth filter plant, although providing the necessary degree of cleanliness, is expensive in first cost and in operation. It is here that electrical engineers can step into the breach by perfecting the electrostatic process, which, in this country, has not yet proved itself superior to the filter plant. It is apparently giving satisfaction in America. Of the wet type, the most promising is the Swarz disintegrator, which appeared in its final form just prior to the war, and which showed promising results combined with simplicity and reliability, but does not lend itself to potash recovery. For rough cleaning, an extremely simple process appears to be meeting with success in America, and may shortly be introduced into this country. I refer to the Kling-Weidlein system, which is dry and involves no loss of sensible heat. It must not be forgotten that the gas requirements for engines and for boilers and stoves are quite different. The sensible heat must be largely reduced for the former, but may be retained for the two latter. Again, the same degree of cleanliness, though desirable for boilers and stoves, is by no means so important, particularly where potash recovery is not included. Reference has been made to the advantages of clean gas for stoves, and I understand one speaker to say that stoves using dirty gas were relined every three months (Does not

this mean cleaned ?), but would run for two years on clean gas. I may add that I have twice been in stoves opened up in each case after five years in operation on clean gas, and in either case the condition was practically as good as when the lining was renewed. There is nothing new in the remarks made by me to-night, and, as a matter of fact, I made almost identical statements before a meeting of this Institution as far back as 1912, and the slides I have shown to-night were selected from a batch exhibited at that meeting. The point I am endeavouring to emphasize is that there has been no material progress made in this country in the utilization of blast-furnace gas since 1912. We may have introduced a few improvements in details of gas engines and have constructed half a dozen or so more engines. We may have even put down one or two new gas power stations, but we have made no material advance. We are indebted to Germany and America for such improvements in gas cleaning as may have been introduced into this country. On the other hand, there are a large number of blast-furnace plants making little or no use of their gas. Some of these plants are isolated (i.e. unconnected with a steel-works) and others still in existence are of so antiquated a type that it is impossible to use the gas at all. I consider Mr. Fowles's paper most valuable, inasmuch as it will serve to bring this quesion of gas cleaning once more before those who are not making full use of the advantages they possess.

Mr. H. J. Gibbons : I propose to confine my remarks to the general aspect of the subject, and not to criticize the scientific data of which the two papers contain so much. I certainly think these papers should help considerably towards the solution of two problems : first, the conservation of coal ; and, second, its utilization to the best advantage. The authors have dealt with electrical power from totally different standpoints. In the one case it is an isolated factory which has developed its own electrical installation and necessarily begins with coal, both for heating and for power purposes. In the other case the production of gas is a stage in the process of manufacturing iron and steel ; gas is in this case a by-product. In the case of the Hoffmann Manufacturing Company, I think the right thing has been done, firstly from the customer's point of view in obtaining electricity at low cost, and secondly from a national point of view in recovering by-products. The figures show that it is certainly possible to generate electric power at a cost comparable with the prices charged by electricity supply undertakings. I am somewhat disappointed with the repair cost in Table 8 of Mr. Patchell's paper. This is apparently 6·28 per cent of the capital cost, and should not be more than half that figure. Probably there is some explanation in that repairs and renewals to various parts of the plant—owing to the fact that suitable materials were originally unobtainable—have been charged to general repairs, whereas the whole of the sulphate recovered has been credited to fuel cost. The cost of lubrication, mentioned last week, has been reduced by one half, and I understand that for 1919 the cost of repairs is less. Perhaps a few remarks on the type of engine installed may not be out of place. They are of the four-cylinder four-crank horizontal type, which have cylinders each 20 in. diameter × 28 in. stroke, and run at a speed of 190 r.p.m. They were made by my firm, the Premier Company, which has been a pioneer in large engines, particularly large-cylinder engines. Engines with 38 in. cylinders were made 18 years ago by the Premier Company, and they are still running successfully to-day. Four such cylinders make up a unit on blast-furnace gas of about 1,800 b.h.p. Captain Pyne spoke of Continental and American development of scavenging. I think it is generally acknowledged that a good deal has been done in this country in the way of scavenging in large-cylinder engines. Mr. Hamilton of the Premier Company was really the pioneer in that direction. Experience has taught us that engines must have multiple cylinders for moderate size units if electrical drive is required, even with direct-current generators, so as to get steady running. For alternators it is essential to have multi-cylinder engines, and the four-cylinder type of engine installed at Hoffmann's gives a sufficiently even turning-moment and low cyclic irregularity to allow it to be coupled to alternators for running in parallel. It runs at a medium speed, and Mr. Patchell's remarks show that this is an advantage in the power house. Even with a lower-speed generator this type is cheaper in capital cost than the high-speed vertical type with its cheaper generator. With this type of horizontal engine the cylinders can be made of such a shape, and the valves can be so disposed, that the best fuel economy is obtained. The floor space is not very much more than that taken up by the vertical type, especially when the pipe arrangement is taken into account in the vertical engine. However, this horizontal multi-cylinder type of engine has its limits, which as far as can be seen at present are in the neighbourhood of about 1,000 h.p. Units have been made up to 750 b.h.p. (500 kw.) with four cylinders. Whilst agreeing with Mr. Patchell that large-cylinder units must be used to obtain larger powers, the other question arises : whether the Continental type does not take up too much floor space and necessitate buildings too large and foundations too heavy. Probably if gas engines are to be used in large units in the future, there will have to be a compromise between the two types.

Dealing with Mr. Fowles's paper, it is of course well known by those who have been working on the problem for years that where blast-furnace gases are available there is no comparison between the gas engine and other forms of prime movers whether for blast or for electrical production—though it needed dear fuel conditions to bring it home, and I doubt if it is yet fully understood in all directions. Many years ago the opinion was expressed that at blast furnaces with steelworks attached, fuel need not be used anywhere except in the furnaces. Gas would provide all the heat, and gas used in gas engines would provide all the power required. In this country, however, the ironworks are often quite distinct from the steelworks, and consequently the power required is small, and Mr. Fowles's paper suggests that if the gas is not wanted for power it could be economically utilized for electrical production and distributed over adjacent areas. One often

wonders why, in such cases, there cannot be co-operation between ironworks and the electric supply authorities, instead of, as at present, gas being used in boilers to get rid of it and power stations being set up in some cases close to the furnaces burning coal in boilers. In such cases the gases should be cleaned for gas-engine use and converted into electricity and distributed. The last speaker spoke of reliability. Both authors speak of their gas engines being equally as reliable as steam engines. I know of a case in this country where a gas engine has run 5 months night and day without stopping. I want to say a few words about some of Mr. Woodhouse's criticisms. He implied, I think, that gas-engine plant for generating electricity would certainly not be installed because coal is dear. Probably his point was that private individuals should not put down their own power plant at all, but should leave it to the large electricity supply stations; but what of the many users who already have their own power plant—in many cases obsolete and wasteful steam engines? Surely it is not wrong to displace these by more economical methods? They are quite justified in saving coal because it is dear. Another point is that a good deal of transport of coal would be saved if power stations could be placed near blast furnaces and electricity generated there. It is an accepted fact to-day that the gas engine is a saver of coal; its high thermal efficiency is undeniable. Mr. Percy Taylor has published a test result on an engine of a similar type to those at Hoffmann's, showing a heat consumption of 7,510 therms per brake horse-power, i.e. a thermal efficiency of $33\frac{1}{3}$ per cent. The only reason why the gas engine is not more generally used is said to be its capital cost, but from a national point of view the right thing to do is to conserve coal. Where coal must be used, the by-products should be utilized. Mr. Woodhouse remarked that ironmasters knew what they were doing. I agree with him that there are a number of progressive ones. In one case over 20 large gas-engine units have been installed for blowing and power, and it is significant that once an ironmaster commences to install large gas engines he continues to do so in spite of the alleged difficulties. There is evidently something in it, and this method of utilization of by-products in the shape of gas has hardly yet been touched in this country. The younger generation of ironworks managers believe that the time will come in such industries when coal will only be used in coke ovens. The coke produced will be used in the blast furnaces. Power will be produced by the gases from the coke ovens and the blast furnaces for use in other departments of the industry, and the surplus power will be sold. Any steam required will be raised from the exhaust boilers of the gas engines. Industries not in the region of this surplus supply must be considered on the circumstances of each case. Where coal is far distant they must reduce the cost of this item as much as possible, and the gas engine provides the way, as surely is now proved by the results at Messrs. Hoffmann's. Within the course of the next year or two we may be able to say that really large units of gas engines can be offered by makers with many years' experience behind them, so that they can be guaranteed to run successfully, even under the most stringent conditions demanded.

Mr. J. Paton: The position with regard to by-product recovery plant is not so favourable as it was before the war, owing to the increased cost of coal and labour not being offset by a corresponding rise in the price of sulphate of ammonia. It is therefore important to see what economies can be effected in the running of the plant. As Mr. Patchell points out, the addition of 25 per cent to the coal bill for the provision of steam for the recovery plant is a very heavy item. In this connection I should like to ask Mr. Patchell if he finds the type of towers which he uses to be as efficient as the ordinary packed towers. From some of his figures it would appear that they are not quite so efficient. I notice he gives the temperature of the air leaving the saturator as about 68° C., corresponding to a recovery of $\frac{3}{4}$ lb. of steam per pound of coal. With towers packed with circular tiles there is no difficulty in getting a temperature of 73° C. or 74° C., giving a recovery of 1 lb. of steam per pound of coal gasified. It is very important that the air should be raised to the highest possible temperature by the hot water used in cooling the gas, as any deficit in the amount of steam obtained in this manner has to be made up by live steam. As far as the saving of steam used in the producer is concerned I think that the "Moore" producer is on the right lines. There is no doubt that Mr. Moore has been able to recover 60 per cent. of the nitrogen in the fuel in the form of sulphate of ammonia, using only 1·25 lb. of steam per pound of coal, against 2·25 lb. or 2·5 lb. in the case of the Mond-Lymn plant. I am particularly interested in Mr. Patchell's paper because I have been connected with a recovery plant of practically the same size, the greater part of which was erected during the war. This particular plant was of the Moore type. A plant having a gasification capacity of 30 tons of coal per 24 hours was installed in 1914; this plant consisted of two producers with the necessary recovery plant; another producer was added in 1917 using the old recovery plant, and a third producer was put down in 1919 with a recovery plant for 30 tons of coal. The cost of this plant was about £10 6s. per kilowatt, which is very much less than the figure stated by Mr. Patchell. Regarding corrosion of the absorbers, I think some very useful information will be found on this point in a paper read by Sir Robert Hadfield before the Iron and Steel Institute in 1916. He showed that the corrosion in steel vessels using acid solution is intimately connected with the proportions of manganese and carbon in the steel, and he gives the proportions which will largely avoid this corrosion. There is one other direction in which a saving in steam can be effected in a plant of the Mond-Lymn or Duff type. It is quite possible to recover the sulphate of ammonia direct either from a mechanical washer or from a tower such as is used in the plant described by Mr. Patchell. I know of a large plant which has been running for about a year recovering the sulphate direct, thus entirely dispensing with the evaporating plant and saving the steam used in the evaporation; this is a very important point. Mr. Patchell mentioned some trouble regarding the dis-

tillation of the tar. The tar from a plant of the Mond-Lymn or Duff type can be easily dealt with. It is necessary, however, to keep the tar in the still agitated until the water is distilled over. This can be done by injecting compressed air into the bottom of the still. I should like to ask Mr. Patchell if the fuel consumption which he gives of 1·66 lb. per kilowatt-hour is the value of the fuel less the net value of the sulphate of ammonia.

Dr. J. A. Harker: Mr. Patchell referred in his paper to my colleague, Mr. H. A. Humphrey, who was during the war a member of the staff of the Ministry of Munitions, and is at present in America. A report has just been issued by the Ministry, which in one of its sections covers much the same ground as Mr. Patchell's paper. The Report of the Nitrogen Products Committee, published by the Stationery Office as a Government blue-book in January, deals *inter alia*, in a way which I think electrical engineers will find useful, with this question of the generation of electric power with by-product recovery. The Committee has examined, partly statistically and to a small extent experimentally, the relative advantages of the use of raw coal and of the various projects for partial and complete gasification of coal with by-product recovery. It has indicated in considerable detail its views on many of the fundamental points on which a manufacturer would like authoritative information before installing a large power plant. If a manufacturer is in doubt whether to purchase electric power or to generate it himself, the first thing he wants to know is what it is going to cost. In the Report is set out in considerable detail both the installation and running costs of the different types of plant, the consumption of coal in each case and so on. The data are set out in such a way as to give an engineer needing guidance all the necessary information regarding by-product recovery plants and the general economics of the problem. I thought it worth while in Mr. Humphrey's absence to direct attention to these figures and to say that many of the conclusions in Mr. Patchell's paper are in accord with the views of the Committee. The general examination of the electric power problem was conducted by a sub-committee under the Chairmanship of Sir John Snell, while the by-product distillation part of the inquiry was carried out by Mr. W. R. Cooper, Mr. J. H. Rider, Mr. Frank Jones, Mr. Humphrey and myself.

Mr. G. Bass: At the commencement the Hoffmann Manufacturing Company perhaps had some doubts as to the results which would be obtained; but now that the plant has run for 2 years and 8 months those doubts have been removed, and I think it will be agreed that the figures given in Mr. Patchell's paper are most satisfactory considering the various sorts of coal which had to be used and the difficulty in connection with labour. From our experience we have no doubt that scrubbed bituminous producer gas, as supplied to plant like that described in Mr. Patchell's paper, is an ideal power agent when used in gas engines, and it has proved itself to be pre-eminently satisfactory for almost every kind of heating work, ranging from the small open burners to the large heating furnaces. The type of gas made from bituminous coal in a simple dependable apparatus and suitable for almost every kind of manufacturing work is well worth the consideration of the engineer of to-day who is contemplating an extension of power or heating for furnaces. In regard to the certainty of operation of the gas engine of a reputed make, one seems fully entitled to claim that both in size and in reliability of operation the gas engine need not be regarded as behind the steam engine for straightforward stationary work such as electricity generation or factory work. In connection with the reliability of the exhaust-heat boilers, we have only had one compulsory stoppage, of 43 hours, in 2 years and 8 months. That stoppage was entirely due to a leaky mud-hole joint, and it was not desirable to shut down the engine at that time to stop this leakage. When we were able to shut down we found that scoring had taken place very badly at the mud-hole joint, and we had to close down for 43 hours to make the necessary repairs. The attention required for these boilers is practically negligible, as they are automatically controlled so far as the water supply is concerned. I was very pleased to hear Mr. Taylor's remarks last week as to the condition of the plant and his favourable impression of the gas plant after visiting the works. One has had impressed upon one, perhaps, that if one has a gas plant it must necessarily follow that one must be up to one's neck in tar. But that is not the case.

Mr. A. H. Lymn: Mr. Paton has referred to this particular construction of washer as perhaps not being so efficient in the recovery of steam from the sensible heat of the gases, and he gave a figure of 73° C. which is obtained with packed towers, pointing out that this means a greater recovery of steam. If 73° C. is an average figure, and if it really represents saturation, it is certainly a greater recovery, but I imagine that the tower to which he refers was part of a plant working continuously at practically full load, whereas at the works of the Hoffmann Manufacturing Company the plant works at full load, or say 80 per cent load, for 8 hours a day, stops two or three times a day, and runs during the night at about one-third load. We have thus not the same conditions to deal with. An important question arises, viz. does Mr. Paton's figure represent saturation, and has he ever made simultaneously with those thermometer readings actual estimations of the moisture contained in the air blast? With similar towers to those to which he refers it very frequently occurs that the thermometer temperature does not represent saturation. I believe that if we were working at full load continuously we should not be behind the figures he mentioned. On the point of corrosion and the recovery of ammonia in steel washers, Mr. Paton suggested that it was due to a particular composition of the steel. I can only say that no particular composition has ever been stipulated for these washers. Probably a dozen of these plants have been put into operation since 1911, and since that time no corrosion has developed in any one of them, beyond such things as bolts, to which reference is made in the paper. A great deal of this I attribute to the design. In those cases of by-product recovery plants where an attempt has been made to recover

the ammonia in a steel washer, it has generally been in a horizontal washer with revolving paddles, having at the same time a long lute in which the height of the liquor fluctuates all the time. If one considers the two constructions, there are reasons why the Lymn absorber is less liable to corrosion than the steel washer of the construction referred to. I am pleased to see from page 418 that Mr. Patchell is converted in the matter of the mechanical grates for gas producers which I recommended to him two or three years ago. It will perhaps amuse him to be reminded of the criticism he made at the time, namely, that he preferred to employ stokers for his producers rather than fitters. I am glad to see he does not think there is such a strong case against mechanical producers now as he maintained then. If Messrs. Hoffmann had been able to obtain the good coals (of low ash content) which they set out to use, the installation of static producers would, however, have been quite justified. I should like to refer again to the particular construction of washer, because the diagram does not show it quite as it ought to be shown. The discs are considerably smaller in diameter than the bottom of the cone. The first plant which I built myself had revolving discs. Owing to the usual sort of thing which may happen, there was a stoppage of the gear, and then I found the washer worked practically as well without revolving the discs. At that time the disc was considerably bigger than the cone; that is to say, the water had to run off the disc on to the cone, and vice versa. Then I was asked to increase the size of the plant by something like 80 per cent. I was confronted with the probability of having to build an additional set of washers. Instead of that I cut pieces off the cone, and kept cutting them off until I was putting the gas from 90 tons of coal through the washer, which had been built for 50 tons. I did this by causing the discs to be smaller than the cone, and they are now constructed in such a way that the water falling on to the top disc would drop straight to the bottom without going on to the cones. It will therefore be seen that it is the momentum of the gas itself which causes the atomizing of the liquid and intimate contact of the gas therewith. Indeed, that is the patented principle of the washer, so that a very thorough wash itself takes place without mechanical means. It would perhaps interest members to know that these washers can be constructed to deal with anything from 10,000 up to 2,000,000 cubic feet or more per hour. Mr. Woodhouse implied that when coal is dear is not the time to install gas plant. I think that requires a little comment. In a way it is true, if when one is putting down plant one does not go into the matter fully, because if one raises the steam for the plant in a direct coal-fired boiler, it would require coal to the value of 5s. to provide steam to gasify coal having a value of £1, i.e. 25 per cent. But what Mr. Woodhouse apparently overlooks is that steam can be raised in numerous ways. It can be raised, if it is in conjunction with a furnace plant, from the waste gases of the furnace. If it is in conjunction with a gas-engine plant it can be raised by means of the exhaust gases. If it is firing a boiler plant, it is possible, if we have a big installation, to make a part of the power plant non-condensing or to bleed steam from one of the turbines. Mr. Patchell later on in the paper remarks that the gas turbine is not a commercial problem. We all agree with him, but it may be of interest if I read a résumé of an article from last week's *Zeitschrift des Vereins deutscher Ingenieure*:—

"The firm of Thyssen of Mullheim prior to the war acquired the Holzwarth gas-turbine rights and built a 1,000 h.p. gas turbine, in all the main respects similar to the one described by Mr. Holzwarth in his book on 'Gas Turbines.' A considerable amount of research was done on this up to the outbreak of war, but this ceased entirely during the war. Since 1918, however, continued research has been carried out by Messrs. Thyssen, and turbines built or under construction include two oil turbines of 500 b.h.p. running at 3,000 r.p.m. and another 12,000 h.p. gas turbine running at 1,500 r.p.m. The vertical construction has apparently been dropped and these oil and gas turbines just referred to are built with horizontal shafts. No mention is made in the article of the reasons why this construction was adopted. Efficiencies so far obtained are comparable with those of the gas and Diesel engine, but these figures were got with the gas and air under a much lower compression than is the practice with reciprocating engines. Very lengthy tests have been conducted and the blades of the turbine have been found, when made of a special soft steel manufactured by Messrs. Thyssen, perfectly clean and uncorroded. Mr. Holzwarth remarks that it is very desirable that there should be no water or water vapour in the gas supplied to the turbine to avoid the formation of sulphuric acid and the consequent corrosion of the blades, but as the temperature is not likely to fall sufficiently low for this acid to be formed, the reasons for the precaution are not entirely clear. The speeds of the turbines are high and, compared with steam turbines of similar power, the diameters are larger. This is because the power is dependent on the size and number of the explosion chambers which are arranged in a ring opposite the blades of the rotor. The former difficulties in the operation of the nozzle valves have apparently been overcome by the use of oil under pressure. The indicated efficiency obtained is claimed to be 45 per cent, while the gas consumption is stated as 2,500 calories per h.p.-hour at full load, with a compression of three atmospheres absolute and an explosion pressure of 15 atmospheres absolute."

Before the war I saw one of these gas turbines running. It was stated to be of 1,000 h.p., but when I saw it it was only doing 300 h.p. I regarded it at that time, however, as a great step in progress to have a gas turbine doing even this amount of power.

Mr. W. Chaney: Some little time back I had a similar problem to consider. It was a question of installing coke-oven plant for the supply of town's gas, and the heating of the ovens by means of producer gas. I had to travel very much along the same road that Mr. Patchell has done, and can fully endorse his figures as regards the economy in the production of electricity by means of producer gas, although my figures were arrived at in a different manner. Instead

of using the high-pressure steam for the manufacture of the producer gas, I intercepted this steam by generating the electric current required for the various plants in connection with the coke ovens, passing on the exhaust steam at atmospheric pressure for the manufacture of the producer gas. Mention has been made of the increased cost of fuel and its effect on the cost of production of producer gas; it must, however, be borne in mind that one ton of coal yields 130,000 cubic feet of producer gas, as compared with 12,000 cubic feet of coal gas manufactured by the ordinary gas-works practice. Assuming the price of coal has risen from 17s. to 40s., the production cost per 1,000 cubic feet of coal gas has therefore increased by 1s. 11d. as compared with 2d. for producer gas, the calorific value of the former gas being 500 therms, and of the latter 130 therms, per cubic foot. I do not think it was the original intention of the inventor of producer gas (Dr. Mond) to use the best coal, and I believe that the war has taught us a great deal as to what fuels may be employed in the manufacture of producer gas. In my own case I have found it possible to dilute the coal by means of coke dust, and by employing 30 per cent of this dust to obtain a yield of 65 lb. of ammonia per ton of fuel gasified. It has been my own, and I think it is general, experience that low calorific gases are not economical when employed for the production of steam in Lancashire boilers. Mr. Fowles has pointed out that there are large quantities of waste gases that might be added to the national power supply, and I would suggest that large cities and towns within the economic area of existing coke ovens or blast furnaces should be compelled to utilize the surplus gases from such plants.

Mr. F. H. Preece: The question of cleaning gas is of as much importance to the boiler man as it is to the gas-engine maker. I confess that I do not understand Mr. Fowles's attitude as to the question of firing boilers with gas. It seems to me that in many ways his figures are rather misleading. He states that it is very bad policy to "gas-fire" boilers. I do not agree with him, nor apparently do many blast-furnace managers from the way they are continually calling for boilers to be blast-furnace-gas fired, and in very large units; they are not asking for 10,000 lb. evaporation units, but for 30,000 lb. My firm has supplied about 1,250,000 square feet of heating surface within the last 15 years. That means, taking 70 per cent load factor, practically about 345,000 lb. evaporation per hour. Then again Mr. Fowles has made a comparison between what he calls the new and the old methods. From the way he puts it, it looks as if the new method must be the method of using a gas engine, and it is only under that condition that one can get a surplus power. But on the old method, he tells us: "Under this latter method"—he is speaking about the power used for the blowers on one furnace—"600 h.p. required half a ton of coal plus 600,000 cubic feet of gas." With blast-furnace gas at 100 therms we can always depend upon 1 lb. evaporation for each $17\frac{1}{2}$ cubic feet of gas. This means that allowing, say, 7 lb. evaporation per pound of coal, about 42,000 lb. evaporation is used to generate 600 h.p. That means 70 lb. per horse-power. Mr. Fowles has shown on the screen an interesting series of graphs; the top graph showed the pressure in the gas main for the uncleaned gas and the bottom one the pressure for the cleaned gas. That has been of great interest to us from the firing point of view. All our experience in this country has been with uncleaned gas. We find we cannot satisfactorily use a burner of the Bunsen type because it gets blocked up. We use almost entirely an external combustion chamber; with this external combustion chamber we have to set our air ports for the higher pressure of the gas, but we have had the pressure vary from 3 inches down to $\frac{1}{8}$ inch (water gauge). One can imagine what is going to happen with a fixed air port with such a variation. We set the air ports for about 3 inches (water gauge). If we have a steady pressure we get possibly about 70 per cent efficiency, but if the pressure drops to $\frac{1}{8}$ inch what is going to happen? It is this variation which has militated against good efficiency in blast-furnace gas-firing over a long run. Now, fortunately, cleaning has come into use, and I think we shall find shortly that all the blast-furnace managers will thoroughly go into the cleaning question and that we shall have clean gas delivered to the boilers and, as shown by Mr. Fowles's graph, the pressure will also be kept within limits. Under conditions of clean gas, we could arrange with Bunsen burners for the air adjustment to be within fine limits. The pressure would be fairly steady and the air naturally in proportion. We find as a rule that with uncleaned gas we can depend upon about 70 per cent efficiency for boiler and economizer. That drops with dirty gas after about 48 hours, supposing dusting is not done at regular intervals, to about 63 per cent. With cleaned gas we see absolutely no reason why we should not get 78 per cent. Probably on test we should get a higher figure, and with such an efficiency gas-fired boilers coupled with turbo-blowers or turbo-generators would give as good a running efficiency as do some large coal-fired stations, because in all these steelworks the load factor will be very good. I should like to refer to one point about the Halberg-Beth system which from the boiler-firing point of view is a disadvantage, namely the cooling. A fair proportion of the sensible heat is lost. I understand we have to cool to somewhere about 180° F. That is going to be a considerable loss in firing. It is going to reduce the combustion-chamber temperature considerably. I believe that on the electrical principle they can clean and deliver with the exit temperature from the blast furnace about 600° or 700° F.

Mr. L. Andrews: I have compared some of the results Mr. Patchell has achieved with the predictions contained in a paper read by my colleague (Mr. R. Porter) and myself before this Institution about 11 years ago, advocating a combination of gas engines and ammonia-recovery producers for generating electric power. I have also compared the thermal efficiencies of both steam and gas plants recorded in our paper with the up-to-date results Mr. Patchell now records. The comparative results tabulated below show that not only have our estimated costs of running gas plants

been greatly improved upon, but also that even greater improvements have been effected in the thermal efficiency of steam plants.

Gas Engine Plants.

	1905 Paper	Mr. Patchell
Assumed plant factor ..	82%	—
Actual plant factor		73·6
Estimated gross coal per unit	2·18 lb.	—
Actual gross coal per unit ..	—	1·7 lb.
Thermal efficiency recorded	15%	19·9%

Steam Plants.

Max. thermal efficiency recorded	9·63%	18%
Average thermal efficiency (20 power plants)	6·83%	—
Average thermal efficiency (6 power plants)	—	11·83%
Average thermal efficiency, all British plants	4%	9%

In view of the greatly improved economy in steam plants recorded above, due largely to the use of much larger steam-turbine units, it is now, in my opinion, more difficult to make out a good case for the use of large gas engines in large electricity-supply stations than it appeared to be when we read our paper. In fact, I entirely agree with the author's general summary that: "For huge plants the steam turbine has no competitor." I think, however, Mr. Patchell has made it very clear that for such installations as he has described there is a big field for the use of gas engines combined with ammonia-recovery plants.

Mr. H. M. Ridge: Mr. Fowles refers to the question of pre-cooling for which, on the plant with which he is connected, water is at times used in direct contact with the gas. It is undesirable to raise the humidity of the gas, quite apart from the trouble it causes in the Halberg-Beth filter plant. There is a good deal of difficulty about the cooling of the gas, because with an average temperature of the gas from the various blast furnaces in the country, somewhere between 212° C. and 300° C., a very large volume has to be cooled down to below 110° C., and preferably to about 100° C. In spite of the number of heat units to be removed and wasted, on balance the result is distinctly in favour of this method of gas cleaning. The Halberg-Beth plant was first used in Lorraine, where the conditions are entirely different. There Minette ores are charged into the blast furnace without drying or calcination, and consequently the amount of moisture present is very large and frequently excessive. While over there last month, I found so much moisture present that water was dripping from the mains in which the gas passes to the dry-cleaning plants. No cooling was required but, on the contrary, an appreciable amount of heating of the gas was necessary before it could be filtered for the removal of the dust. In spite of that the Halberg-Beth dry-cleaning plants have made considerable progress in the Lorraine district, and it will be of interest to recall the practice of Hagondange, one of the newest iron- and steel-works there. They have six blast furnaces, a number of steel furnaces, complete rolling-mills, and roll steel sections. The whole of that plant is run without the use of a single gas producer, depending entirely upon electric power generated from dry-cleaned gas, there being, after the utilization of the gas necessary for the stoves of six blast furnaces, sufficient surplus to heat the steel furnaces—of course in addition to the blowing engines and the power required for blast furnaces—but to supply ample power for the rolling-mills and to leave a margin from which the surrounding district is supplied with light and some power. As a consequence of the present conditions prevailing in Lorraine, with the acute shortage of fuel, a large number of blast furnaces were shut down. Hagondange is barely able to work two furnaces out of six, and as a consequence they do not get enough surplus gas to run their plants efficiently, so that their rolling-mills can only work intermittently. Mr. Woodhouse has referred to the position in this country, and a number of speakers have dealt with his remarks. I should like to carry the matter a stage further. I have mentioned one particular instance in Lorraine. I could give a whole series of similar instances in Lorraine and other parts of the Continent. Here, on the other hand, we have a number of blast-furnace works even without steel-works and without an outlet of their own for electricity, where coal is still being burnt under boilers to generate steam. The reason is interesting. The gas from the blast furnace is laden with dust and so dirty that the boiler efficiency is very appreciably reduced after only 2 or 3 hours of work, and to obtain enough steam the ironmasters have to fall back upon coal firing. The flues of the boilers are nominally cleaned out once a week, but that work is seldom done thoroughly, and, even if it were done properly, the results would only improve for a few minutes. However, that is not the worst, because in some blast-furnace plants in this country we still have open-topped furnaces where the whole of the gas is wasted. Another phase of the question of using uncleaned gas is that it has deleterious effects on the blast-furnace working. A large quantity of gas has to be burned in the stoves for pre-heating the blast. I have recently gone through the records of one of the works in this country, where the average life of the brickwork of the stove is 3½ to 4 months, necessitating not only a large amount of new brickwork, but also an enormous waste of labour for relining and packing. This is caused by the highly corrosive action of the potash and other salts. In other works in the country using the Halberg-Beth system, stoves have to-day been in continual use for over 2½ years and are still in good condition. In another case they have been in use for a longer period without ever having been touched. That is important, but from the electrical supply point of view the question has to be carried further, because with the cleaned gas we get a higher combustion temperature in the stove, so that a much smaller quantity of gas is required and a large amount remains available for use in gas engines and for power supply. The author repeatedly mentions 1,000,000 cubic feet, but this is not to be taken as a standard hourly production of gas per furnace. There are many furnaces working with

1,500,000 cubic feet per hour and more. I would ask him a question regarding his analysis of gas-engine exit gas, in which I think I am right in saying he quotes 8·3 per cent oxygen as being present, which would correspond to a surplus of approximately 40 per cent of air. Is that due to insufficient mixing, or is it due to an attempt to reduce the temperature in the gas engine by an excess of air? I would also ask Mr. Patchell about his figures of producer-gas analysis. He shows an average of 15·8 per cent CO_2 and 26·6 per cent of hydrogen. Perhaps he will tell us how the ammonia recovery was affected by a smaller quantity of CO_2 in the gas and a decreased amount of hydrogen.

Mr. T. M. Hunter (*communicated*): Mr. Fowles has described one of the most modern blast-furnace power plants in this country. The conditions of the power plant before the alteration were evidently among the worst in the country. It would be interesting if the author would give some notes on the difficulties encountered in running the plant, and on any accidents which have occurred. At one ironworks in the North—possibly the plant described—it is understood that the whole power plant was brought to a standstill for a number of hours through all the dust bags in the gas-cleaning plant being clogged up simultaneously with mud, due to deposition of moisture out of the gas. The possibility of such an accident is a serious thing to have to face. The cleaning of blast-furnace gas is still in its infancy. New processes are continually being evolved. The Halberg-Beth process gives at present the greatest degree of cleaning—making the gas considerably cleaner than is needed for use in stoves and boilers. The cost of the plant, and of the power required to run the plant, is higher than that of any other system. Another disadvantage of this system is that the gas must be cooled to about 70° C. Gas must in any case be cooled before it can be used in gas engines, but it is an advantage to have the gas hot when it is to be used in boilers and stoves. Knowing that the gas is supplied from a blast furnace at anything up to 400° C. or even more, and that the sensible heat in the gas amounts to from 10 per cent of the total calorific value at 250° C., to 16½ per cent of the calorific value at 400° C., we see what a loss is involved in this system of cleaning the gas. Comparing the power raised by the use of cleaned cooled gas in gas engines, and that raised by the use of hot cleaned gas burned efficiently in boilers supplying modern steam turbines, it is found that the amount of sensible heat which is lost in the former method is almost enough to make up the difference in overall efficiency between the two schemes. This assumes that an efficiency of over 80 per cent is got in the boiler plant, and this efficiency can be confidently expected. A recent installation at an ironworks in the Midlands consists of three large Lancashire boilers fitted with special gas burners. Superheaters and economizers are also fitted and uncleaned hot gas is burned. The boilers supply steam at 160 lb. pressure and 75 degrees C. superheat, to a turbine blowing-engine. The full tests of the combined plant have not yet been completed: but tests which I made upon the steam-raising section of the installation showed an efficiency of about 78 per cent, taken over boilers, superheaters, and economizers. This was reached while still using uncleaned gas; but the burners are specified as being suitable for the use of hot cleaned gas, when the proposed electrical gas-cleaning plant has been installed. The use of cleaned gas will give a considerable improvement in this installation: but of course the best results would be attained when using large water-tube boilers, owing to the saving in radiation and other losses. The gas-cleaning plants at present available, which give cleaned gas without reducing its temperature, are the Lodge, the Cotterell, both electrostatic plants, and the Kling-Weidlein plant. The latter consists of a filter made of a mattress of fine steel turnings, suitably compressed, through which the gas is passed, and the mattress is mechanically shaken at intervals to throw the dust into the hoppers below. This plant is the cheapest of all, and requires the least power to run. Should it prove satisfactory upon prolonged trial, it will bring cleaning of gas within the reach of every ironworks. Of course, hot cleaning of gas leaves in the gas all the moisture which enters the furnace with the ore, and in some cases this is a serious matter. It is very much easier to extract this moisture before the ore enters the furnace than to get it out of the gas later. In the Middlesbrough district some firms are putting in plant to dry their ores, their primary object being to attain the greater economy in coke which is possible if no moisture is present in the furnace. Another point not touched upon by the author is that of the savings to be made at the Cowper stoves by the use of cleaned gas. He assumes 40 per cent of the total gas made as required at the stoves: but this figure can be reduced to at most 33 per cent with cleaned gas and modern gas burners, and this shows a further very large saving. It is very possible that a considerable proportion of the saving made by the new installation should be credited to the saving made at the stoves, although apparently no measurements have been taken there. One other matter should be brought before engineers who are looking to blast-furnace plants as a source of steady power supply from surplus gas. It is quite impossible to compare a blast-furnace plant as a source of power from surplus gas, with a large producer plant, even if the blast-furnace plant consists of a number of furnaces. It is well known to all who have to do with blast-furnace plants that the quantity and quality of gas vary very greatly from day to day, depending on the kind of iron made, on the state of the furnaces, and on the peculiarities in working of the furnaces. The effect of bad working of the furnaces is easily seen in an old-fashioned plant. The gas pressure falls in all the mains. Steam pressure falls. The quantity of blast supplied to the furnaces is therefore reduced, and the output of iron falls off. In the modern plant, having at all times surplus power, there would never be this reduction of output due to lack of blast; but it would still be impossible to avoid the loss of power due to the variations in the quantity and quality of gas available; and the difficulty from the power engineer's point of view is that he must bear the whole of this variation at his power plant. If he

uses gas engines he is helpless; but if he uses steam turbines he can supplement his steam supply by coal-firing. In a modern installation with large water-tube boilers, mechanical stokers could be fitted, which could be quickly started whenever necessary. This would avoid the great difficulty of providing labour for temporary, and perhaps frequent, hand-firing operations. From meeting very many blast-furnace engineers, I am certain that power plants, to take surplus gas or steam, will be anything but welcome to them. In one case, whenever the furnaces were working badly and too little low-pressure steam could be supplied, high-pressure steam from the works' boilers had to be supplied to make up the deficiency, and this was a very common occurrence. So bad is the case, that the output of iron from the works is seriously reduced as a consequence of shortage of steam, although, all the time, coal-firing is being used to supplement the steam raised. This is anything but a modern plant, but it gives an example of what is really a misuse of the power from a blast-furnace plant, under the misnomer of "surplus power."

Mr. N. E. Rambush (*communicated*): Being intimately connected with the building and working of the Lymn power-gas plant at Chelmsford, I have no special comments to make upon Mr. Patchell's paper, as it stands. In my opinion the results of the Hoffmann installation prove that, from the point of view of thermal efficiency, power production by means of producer gas has not yet been placed in the background by any other power motor. In times like these where it is necessary to utilize every available part of the energy obtainable from our fuel supplies, the further possibility of increasing the thermal efficiency of a power plant should not be neglected, and in this connection it may be of interest if I explain in which way I think further improvements can be obtained in the overall efficiency of a gas-power plant. Some time ago I had the opportunity of supervising some tests in connection with working gas engines using hot jacket water in the works of the Power-Gas Corporation at Stockton-on-Tees. The object of the tests was to establish whether it was quite safe and easy to maintain constantly a temperature of the cooling water in circulation in the gas-engine parts between 80° and 90° C. It will be realized that if such hot water can be obtained from running the gas engine, this water can be used for washing the air going to the producers, thus saturating this with water vapour; the hot jacket water having thus been cooled the water can again be used for cooling the gas-engine parts. For instance, with a properly designed air saturator of the Lymn type, hot water at 90° C. will, if present in sufficient quantities, enable a blast saturation temperature of about 85° C. to be obtained. The amount of heat absorbed by the cooling water of gas engines varies with the type of engine in use, but it is generally not below 25 per cent, and not above 40 per cent, of the heat which is contained in the gas supplied. If therefore this quantity of heat can be obtained in the shape of water at 90° C., all the steam required for a by-product producer-gas plant can be obtained from the circulation water, without the aid of either exhaust gas or direct-fired boilers. The experiment carried out in Stockton was to prove whether, by circulating the water through the jackets at a very much quicker rate than is the usual practice, it would be possible to maintain the gas engine in proper working condition. A 100-h.p. horizontal National gas engine was worked for about one month, the jacket water being circulated between the gas engine and an open tank, part of the water being run away to maintain the jacket water at a constant temperature. The experiments established beyond doubt that during working it was quite safe and easy to maintain constantly a jacket water temperature of 80° to 90° C. Several times during the experiment the engine piston was withdrawn and no traces of carbonized oil were found on any of the internal surfaces. The advantages of utilizing hot jacket water in an air saturator, saturating the air blast for by-product producer, will be obvious, since the steam from the exhaust gas boilers will then not be required for the gas producers and may be available for generating further power. In other words, by installing a combined gas and steam power-station fitted with gas engines with exhaust gas boilers, the steam from which is used in condensing turbines, the total power-production capacity of the station could be increased by 10 to 15 per cent without the cost of any extra fuel. The extra cost in adding a jacket-water circulation plant will be negligible in such cases where the gas engines are fitted with water-cooling plant and water-circulation pumps, since the air saturator would itself form a water-cooling plant for the jacket water.

[The authors' replies to this discussion will be found on pages 458 and 460 respectively.]

Tees-side Sub-Centre, at Middlesbrough, 8 March, 1920.

Mr. R. H. A. Coulson: In regard to the consumption of coal, Mr. Fowles must admit that there is very great room for improvement, for he mentions something like 80 tons of good coal being used per week for the boilers on one furnace. That means 240 tons per week with three furnaces blowing, and I think that would so scare most blast-furnace people that they would have taken some steps to obtain the results described in the paper. I saw the gas engines tested and I was very much impressed by their excellent running. The author has described the Halberg-Beth gas-cleaning plant. The capital outlay is very large and there has not been an adequate return on it as far as blast furnaces are concerned. Electrical engineers have perhaps not realized that blast-furnace gas is such a valuable asset, and we have confined ourselves mainly to the steam plant; and if there is an idea that the blast-furnace side should carry the capital expenditure which is involved in the distribution mains for their own electricity supply, I do not think the blast-furnace people

are prepared to face that at the present moment. It seems from the paper that in the author's case there is a public supply company whose large stations could be used to deal with the week-end load and thus effect a great saving of fuel and wages. That is a point which electrical engineers want to take very much to heart. With regard to the balance sheet at the end of the paper, relating to a comparison of 303 electricity works and the estimated waste gases of 50 blast-furnace plants, the author assumes the capital cost per kilowatt of plant capacity at £67 * in the case of the electricity works and £17·7 in the case of the blast furnace, which he qualified by saying that it was a pre-war figure. We were accustomed to figures nearer £6 than £67. My experience of gas engines is that £17·7 per kilowatt is a very low figure, and I should like to know whether it includes the cost of installing a gas-cleaning plant or whether it refers merely to the gas engine. It is very pleasing to me to know that such excellent results have been obtained with gas engines. I myself have very strongly advocated gas engines for all purposes, but I am still doubtful regarding their use for electrical generation, because, up to now, the size of the units is so small compared with a large turbine installation that it is very questionable whether modern turbines and boilers might not be desirable for the generation of power, concentrating on the gas engine itself for blowing purposes. The whole matter turns upon the cost.

Mr. H. Hobson : I think everyone will agree with Mr. Fowles when he points to the importance of using blast-furnace gas much more fully and efficiently than has been done in the past, and there is now general agreement that some form of cleaning is essential, whether the gas is to be used in gas engines or under boilers for turbines. I was very pleased to hear Mr. Coulson's remarks on the question of gas engines versus turbines, and I agree with him when he says that for blowing engines there is a very good case indeed to be made out for gas engines at the present time, but I should hesitate to go quite as far as Mr. Fowles when it comes to a question of electrical generation. There are one or two points in the paper which make one a little doubtful. For instance, I notice they have installed, at the works described, seven gas-engine sets, each of 1,000 kw. capacity, and that the average number of sets working is four. It would therefore appear that their experience has led them to think it necessary for safety to install about 75 per cent of spare plant. That does not seem to agree with the author's figures of plant capacity given in Table 8, which suggest that the generating plant installed for 50 blast-furnace plants is very much less than what would be required at the 303 generating stations dealing with the same total output. I should have thought, at the present stage of gas-engine design, that quite as much spare plant—if not rather more—would be desirable. It is not quite clear what therms per horse-power the author uses in his calculations. In one place on page 432 he says 74,560,000 therms will give 6,500 h.p. (which I take to be brake horse-power) in modern gas engines, but he says a little lower down that 800 h.p. requires 15,000,000 therms, while a line or two further on 150 cubic feet of gas are stated to be equivalent to 1 kw.-hour. These three statements lead me to the conclusion that 1 b.h.p. in modern gas engines requires (1) 11,500 therms, (2) 18,750 therms, and (3) 10,700 therms ; and much of what follows in the paper depends on which of these figures is taken as correct. On page 431 the author states that the proportion of gas required for the stoves under the old method is about 40 per cent. On page 432, under the heading of "New Method," he has taken the same, 40 per cent of gas for the stoves. I have always understood that the figure for ordinary uncleaned gas, making allowance for loss due to pressure regulation and so on, was more like 50 per cent of the gas. On the other hand, 40 per cent is a fairly generous figure to take when we have clean gas, so that the author might really have made more capital out of this point in his comparison. I should like in conclusion to ask one or two questions. Can the author give the actual maximum number of continuous hours running which he has obtained from any one gas-engine generator, and also the total running hours per annum of each generator set and the normal load at which each works ? These points are of importance because I have an impression that, whereas high-speed engines may run quite satisfactorily for a day, or possibly two days, on full load they have not been found to run week in and week out in the same way that a turbine can do. There is also one point with regard to the Halberg-Beth plant. I notice that the gas is cooled in pre-coolers first and after that again heated in a pre-heater. The author did not mention how that pre-heater is heated. It occurred to me in looking at the diagram that the pre-heater might be designed on the lines of certain coke-oven by-product plants as a heat exchanger, that is, one could use some of the heat from the dirty gas to re-heat the clean gas after going through the pre-cooler.

Mr. E. Hall-Brown : The paper seems to advocate increased economy in the use of gas in iron and steel works, and that the gas so saved ought to be used to reduce the week-end load in our power stations. I am afraid if I were a power engineer and responsible for the running of a power station, I should want my Sunday load as well as my week-day load in order to keep down the costs. Is it suggested that the steel-works are to run the whole of their generating plant to its full load on Sunday ? If so, when are they going to overhaul and repair their plant ? There is this to be remembered, that the gas engines described in the paper are engines which are easy to run ; they have small cylinders and run at a fairly high speed. I have always held the opinion that any type of internal-combustion engine will give comparatively little trouble provided the size of the units is small. If we have a number of 12-inch cylinders forming a 1,000 kw. engine we are well within a manageable size. When we come to large cylinders, however, our troubles are very much increased. It is the old story of the motor-car engine which neither wants very much cooling nor very much attention. If we keep to 12 in. to 15 in. cylinders we escape many troubles, whereas in a very large engine we have to face mechanical and metallurgical problems which increase in difficulty with the increase in dimen-

* Since corrected.

sions, and the cost of the engine per unit of power developed is increased enormously. I think it was Sir Dugald Clerk who pointed out that large gas engines never could be made to pay the manufacturer so well as small ones, and he is reported to have said that while he was connected with any gas-engine manufacturing concern they never would make large units. From the fact that the National engines described in the paper are of small dimensions I gather that he is still of the same opinion. I am very sorry indeed to say that to my mind the internal combustion engine of to-day is an extremely imperfect tool; even so, it is not to our credit as engineers, and still less to our credit as ironfounders, that we cannot make large gas engines so well in this country as they are made on the Continent. It is probably a question as much for the foundry people as for engineers, but beyond and above that the important fact must be realized that a gas engine of large power is not a possible proposition. When we compare a turbo-electric generating set of 35,000 kw. capacity with the number of gas engines that would be necessary to develop the same power, we shall at once realize that a big power station for generating purposes is not at present a possibility.

Mr. A. H. W. Marshall: The paper, it seems to me, lacks comprehensiveness in that Mr. Fowles does not give us a complete description of the works or the fuel requirements generally. For instance, he omits to say whether any of the gas is used for heating the steel furnace, or whether coal is used on the boilers for producing steam for the rolling mills, or whether there are any steam-driven mills. Without such information one cannot come to any definite conclusion as to the commercial value of the surplus gas. Then, again, the comparison which he makes at the end between the surplus heat of a number of blast furnaces and the requirements of 303 electricity works, seems to me to be only a comparison. He surely does not advocate that the gas should be used to displace the coal consumed at these electricity works. If so, where is the power to come from for the blast-furnace auxiliaries—the steelworks and so on. It is generally understood that if the gas from the coke ovens and blast furnaces is properly used on the steel plant—and in a few years time there are not likely to be many isolated blast furnaces—there is practically no surplus at all. That is to say, if we take all our gas to the steel furnaces and soaking pits and do all our rolling electrically, we absorb practically all the power that can be got from our blast furnace and coke-oven gas, however efficiently it is used. I cannot make out whether the load curve shown in the paper deals with all the requirements of the steel plant. For instance, taking Fig. 2, if about 1,800 kw. is absorbed by the blowing engines, that leaves only about 1,000 or 1,500 kw. for the rolling mills. Then, again, the discrepancy in the figures for the thermal efficiencies of the gas engine should be cleared up. The author takes 15,000 therms in one case and, I think, 24,000 in another. It is most important that we should ascertain what the actual gas-engine consumption is in practice with a modern plant.

Mr. A. E. Alcock: Mr. Fowles has confined his paper to rather narrow limits. He has made out a case for the utilization of blast-furnace gas to the fullest possible extent, but I fear he has considered his subject entirely from the gas-engine builders' standpoint. It certainly ought to be considered criminal to-day to waste blast-furnace gas. The author has eulogized the Halberg-Beth gas-cleaning system. At the same time it is not by any means agreed that it is the best system. Investigations are still being made, and I hold the opinion that the wet-cleaning type is simpler and better. In fact, in works in this neighbourhood wet-cleaning plant is being installed at the present time. The complication of the Halberg-Beth plant is very considerable, entailing close supervision and heavy upkeep. As to the comparison between gas engines and steam turbines, I think the best case for the turbine driven by steam, generated by blast-furnace gas, is that it has been shown to be nearly equal to the gas engine under good conditions—perhaps not quite. This applies, of course, to large units with boiler pressures up to 450 lb. and high superheat. Personally I am much in favour of the gas engine, but for the purpose of argument I take the other side for the moment. I am afraid the inefficiency of the old system of utilizing the gas is much exaggerated by the author when he states that to run one engine of 600 h.p. on steam raised by waste blast-furnace gas, supplemented by coal firing, 0·6 million cubic feet of gas plus 0·5 ton of coal per furnace per hour would be necessary, thus making out that a modern gas-engine plant is 10 times as efficient as the old steam engine and boiler plant. With regard to the need to supplement the gas by coal-firing the boilers, from my experience with works in this district this is only necessary when the furnaces are working very irregularly, and when such is the case the effect on the working of gas engines would be disastrous. The statement that such an amount of coal is required is thus misleading. Further, in taking a comparison between gas engines and turbines the very heavy capital cost of the gas engines is a factor which must be borne in mind, and they are very sensitive to the frequent changes which take place in the blast furnace, especially where the plant is a small one (say three furnaces or less in blast). Mr. Marshall has alluded to the fact that any excess of gas from the blast furnaces and coke ovens should be used at the steelworks. He ought, however, to remember that not every blast-furnace plant in this country has a steelworks attached.

Mr. J. R. P. Lunn: I should like to say a word or two with regard to the reference made by Mr. Fowles to public electric supply costs. In comparing the costs of the 303 electricity works and the estimated cost of utilizing the waste gases from the 50 blast-furnace plants, it appears that the author has taken the capital cost of the distribution systems, as well as that of the generating plant, in arriving at the figure of £67 * per kilowatt. Even including the distributing systems, £67 is much too high a figure unless the majority of these stations are small and used principally for lighting supplies. In the same way the working costs per unit quoted in the paper probably include all distribution

* Since corrected.

costs, that is to say, they are costs per unit sold, which is quite a different figure from the cost per unit generated. It ought also to be pointed out that a large number of very small generating stations are running on a bad load factor, and this would probably account for the difference between 0·87d. and 0·3d., which is the cost given for the blast-furnace generating plant in 1911–12. I may say that several steam-driven generating stations fired entirely with coal were generating at a cost per unit less than 0·3d. in 1911–12.

[Mr. Fowles's reply to this discussion will be found on page 460.]

North-Western Centre, at Manchester, 9 March, 1920

Mr. H. Pilling : Many electrical engineers, and many steam engineers also, have an idea that the day of the large gas engine is past. Certainly that appeared to be so five or six years ago, but during the war great developments have taken place in this country. A considerable number of large gas engines have been made, very largely because of the cessation of German competition, and the position is now quite different. There are running in this country a large number of engines of very considerable power, about 2,000 h.p. each, both for electricity generation and for air blowing for blast furnaces, and it seems clear from the present papers that considerable openings for development exist with producer gas as well as with blast-furnace gas. Messrs. Galloways have had no special experience of producer gas except with one engine of about 1,000 kw. capacity which ran for four or five years on Mond producer gas in the Midlands and was then dismantled after the cessation of the war. It has now been transferred to an iron company near Middlesbrough and is being converted into a blast-furnace blowing engine. Mr. Fowles might have mentioned that the installation referred to in the paper is at Messrs. Palmer's shipbuilding yard. The station and its upkeep reflect the greatest possible credit upon the firm and the engineering staff. I have in mind other firms where such satisfactory results have not been achieved. It is extremely disappointing to an engine-maker who has supplied engines of good quality to know that the good results obtained in one case are not so fully obtained in another. The reason is usually quite clear. Good running depends to a very large extent on the efficiency of the gas-cleaning plant. It has been shown that with the Halberg-Beth dry cleaning process uniformly clean gas can be obtained provided reasonable attention is given by the engineer in charge. Evidently such reasonable attention is being given at Messrs. Palmer's works. Uncleaned gas is usually so dusty that it is cloudy and puts dust into the boilers at such a rate that the boiler efficiency rapidly falls off and hundreds of tons of dust have to be cleaned out in the course of a year. If the Halberg-Beth cleaning plant is put down in such a case the gas can be made more pure than the air which the men breathe. It is pleasant to hear that the gas valves of the Palmer gas engines are cleaner than the air valves. As I mentioned in a paper read before the North-East Coast Engineers some time ago, this points to the necessity in the near future of cleaning the air as well as the gas. I have no doubt that the long cleaning periods which have been established by the Palmer Shipbuilding Company could then be further lengthened. If an engine of such large size—in Messrs. Palmer's case it has 46 in. cylinders, 4 ft. 3 in. stroke—can run 12 months without cleaning under the present conditions, I have no doubt that with cleaner gas and cleaner air it would be able to run for two years. There seems to be no mechanical or physical reason why an engine should not so run for indefinite periods provided proper cleaning plant is installed. Mr. Patchell referred to the size of units and the two types of engines which a purchaser has to consider. I may be prejudiced in this matter but the decision appears to me to turn mainly upon the question of finance. If a firm has the necessary resources we find the management as a rule more disposed to take the long view and to have the low-speed set. If, on the other hand, there are extensive demands on their capital and they have an exceptionally large programme to carry out, the decision is more liable to turn in favour of the high-speed set. In the case of steam engines for heavy duty, this long battle of types had one definite result, that the high-speed type was entirely ousted in favour of the low-speed sets. It was ousted for this reason. In cotton mills it is of vital importance that not a second should be lost in the course of a year's work and there must be many cases in the Manchester, Oldham, and Bolton districts where the low-speed engine has an absolutely unblemished record over a period of 10 years, not a minute having been lost. It would be extremely difficult to find such a state of affairs with regard to high-speed enclosed engines. Some time ago Sir Dugald Clerk rightly pointed out that a high-speed multi-cylinder engine could be manufactured more cheaply than a low-speed engine. If one considers the matter from the principles of proportion—the weight of the engine in proportion to the cubic capacity and in proportion to horse-power—there are theoretical reasons why the low-speed single or double cylinder long-stroke engine should be heavier for a given power than a multi-cylinder engine. It is cheaper to make a high-speed multi-cylinder gas engine for any given power than it is to make a low-speed gas engine. Moreover, the former occupies less space. On the other hand there is a great difference in maintenance costs. Thus, the whole question appears to turn upon finance, and that is the great difficulty which the low-speed engine-makers are up against. It is always interesting to find some manufacturers deliberately producing a costly article and finding a market for it, and another group of manufacturers deliberately producing for the same purpose a cheaper engine and finding a ready market for that also. Mr. Patchell speaks of 3,000-h.p. engines. I may say briefly that there is no difficulty to-day in producing

in engines with two cylinders 3,000 h.p. quite readily, and with two cranks and four cylinders 6,000 h.p. It is highly probable that if the price of coal continues to rise blast-furnace gas engines will be compulsorily used by order of the Government to utilize blast-furnace gas to the full extent.

Mr. T. R. Wollaston: During the war much was said and written in regard to the future possibilities of gas, but such remarks were confined almost entirely to coke-oven gas and low-temperature distillation gas, with the obsession of valuable by-products. In regard to coke-oven gas Mr. Patchell has told us that it has limitations. So far as we get waste gas from the coke ovens by all means let us use it, but, considered from the point of view of producing any large amount of electricity, coke-oven gas is an impossible proposition; in order to meet the demand in that way we should have to produce more coke than the whole world would want. In regard to low-temperature distillation, there may be big possibilities from the point of view of producing benzol, tar, and possibly good household fuel, but certainly one does not see much scope for it in generating electricity wholesale. I have had recently a visit from an engineer to the South Staffordshire Mond Gas Company who gave me some figures which may be of interest. He said he had a "Premier" gas engine of 300 h.p. which had been working for seven months without stopping. That is a very good testimonial for the gas engine. I would generally endorse Mr. Pilling's remarks regarding choice of gas engines. The big gas engine may be a reliable possibility, but it is a question of capital cost and amount of space needed as compared with the modern steam turbine. The engineer to whom I have referred above gave me the following particulars which have been confirmed by remarks made during this discussion. The coal cost to the South Staffordshire Company was formerly 4s. per ton. It is now 28s. The sulphate yield was 85 lb. per ton. It now averages 65 lb. The gas was sold at an average price of 1½d. per 1,000 cubic feet; to-day the average price is 9d. per 1,000 cubic feet. In spite of all that has been said I have very great faith in the future of producer gas not only for gas engines but also for firing boilers. Even with the present prices of coal and sulphate I am convinced there is a very big future for it. I have been very interested in this subject for the last 10 years and have a plant, on a full-size scale, now half completed. I hope that before the end of the year it will be working within 4 miles of this room. Mr. Patchell has given the figures for coal consumption, including generating steam, for producer work. I see no scientific or practical reason why one should not get a recovery figure equal to Mr. Patchell's without this extra steam and with the percentages of carbon monoxide and hydrogen reversed; in other words to get the same ammonium sulphate with what would generally be called a "non-recovery" gas. The plant which I have mentioned should be able to work with practically any coal that might be delivered.

Mr. J. G. Walthew: Reference has been made to the injurious effect of sulphur gases escaping from the gas-engine cylinders and coming in contact with the electrical equipment. That statement should be challenged, as it would entirely depend on the type of gas engine installed. With gas engines having open-type pistons, and where the liners and pistons are badly worn, it is possible for escaping gases to get into the engine house and so affect the electrical equipment. But that was not the case with the enclosed type of gas engine illustrated on the screen to-night. The engines shown were of the "National" vertical tandem type with totally enclosed crank-case; and should there be any leakage of gas past the pistons into the crank-chamber, such gases are readily drawn away by means of a small exhauster fan, which also assists in promoting a free circulation of air through the crank-case. That is an important point. There is no doubt that blast-furnace gas offers a very much easier proposition for the gas engine than does producer gas, the reason being that blast-furnace gas is of a more consistent quality. After removal of the dust, blast-furnace gas is especially suitable for use in gas engines. It was very gratifying to hear Mr. Fowles state definitely that from his own experience he considered the gas engine to be as reliable a prime mover as the steam engine. I heartily agree with that statement. If any trouble does arise, it is due in the great majority of cases to the gas. That is certainly the case with regard to engines operating on producer gas, and in this respect the gas engine is well ahead of the gas plant. More research work is needed in this direction—that is from the gas producer standpoint—and it would be of enormous benefit to the internal combustion industry as a whole. One speaker has stated that the choice between gas engines of the low-speed and high-speed types was determined by the capital cost. I do not agree. Electrical engineers and power-plant users generally will adopt the type of prime mover that offers the best all-round advantages, and in any case the difference in cost between these two types is not very marked. A most important advantage with the multi-cylinder type of gas engine is its suitablity for electric driving, and especially when operating in parallel. A further advantage is the ease with which a multi-cylinder engine can be started up, as compared with the low-speed German type of engine referred to. Something ought to be said about standby plant. The power station should be properly equipped in this respect, so that at any reasonable moment it is possible to close down any single unit and to overhaul it if required. On the question of recovery of sulphate from gas-producer plants, I was recently at a mill where a gas engine was operating on a 600 b.h.p. load. Notwithstanding the increased cost of labour, and that the men engaged at the gas plant would not do the same amount of work as formerly (three men being employed instead of two), the receipts from the sulphate paid all labour costs, leaving the fuel only as the net charge on the power plant. The normal hours of working were 48 for the week.

Mr. W. Fennell: I represent the undertaking at Northwich which has been running on Mond gas with open-type engines for 21 years. The corrosion of brass and copper due to exhaust leaks in the engine room can be got over. If the contacts are regularly covered with

vaseline there is not much trouble from that cause. In connection with the Wednesbury undertaking using Mond gas we had quite as much trouble with the enclosed type of engine as with the open type. The oily fumes escaping from the crank chambers are churned up by the flywheel and condense on the dynamo windings in the form of an oily deposit very difficult to remove. One speaker has suggested that the use of an exhauster fan, discharging from the crank-case to the outside air, gets over the trouble. I have found this to be the case, but it also uses an immense quantity of oil, and I have found it better to use a ventilating pipe without a fan, so striking a happy medium. Those who have had to do with producer-gas engines know that the crux of the whole question is the tar which is left in the gas. It is a curious thing that some cleaning plants leave a much greater quantity than others. At the works in South Staffordshire situated over 4 miles from the Mond producers we had a quantity of tar deposited at every point where the gas velocity changed. The inlet valve, the governor valves, and even the regulator valves were often put out of action by it and very frequent cleaning was necessary. At Northwich where we are within a quarter of a mile of the Mond producers we have no trouble at all with tar. In South Staffordshire we got over the trouble to a great extent, on the lines indicated by the last speaker, in a very simple way. We reduced the temperature of the incoming gas below the figure which it would ever reach again by putting a nozzle into the gas-supply pipe discharging it into a medium-sized chamber. The high velocity of the gas emerging from the nozzle produced the desired low temperature and most of the tar was deposited in the chamber, which had a water seal. Of course in dealing with the finance of by-products gas producers we are up against the present-day labour conditions. The cost of running has increased enormously within the last few years, but not so much, I think, as the South Staffordshire Company's figures would appear to indicate. One must remember that the South Staffordshire Mond Company has distribution costs and losses over an enormous area, a good deal of it subsiding, and on the top of their generating and distributing costs the Company has an enormous capital outlay to pay interest on. I have before me the figures of a Mond plant which in six months produced 1,197,000 thousands of cubic feet at a cost of $3\frac{3}{4}$d. per thousand cubic feet, which is very different from 9d. Recently I went into this question of producer gas and I found that at the present day it almost always pays to put down a non-recovery plant or anthracite plant in preference to a by-product plant. Whether the present relative levels of the prices of coal and sulphate of ammonia will be maintained by the Government for long is of course another matter. At the present day one can get quite good costs on suction plant, and the gas-engine power station of from 1,000 to 2,000 kw. is a formidable obstacle to bulk supply. This is assisted, I believe, by the fact that the price of anthracite has not increased during the war in anything like the same proportion as ordinary coal. It can be bought in this district at £2 5s. to £2 10s. per ton by the single truck, which compares very well with the cost of bituminous coal. In his table of costs (No. 8) Mr. Patchell puts down for capital charges 0·207d. per unit on a 75 per cent load factor. On the usual 25 per cent load factor it would work out at nearly $\frac{3}{4}$d. per unit. This is due to the enormous capital outlay of £50 per kilowatt, most of it attributable to the recovery plant. Mr. Patchell could have done the work with non-recovery plant for about £25 per kilowatt and it would of course have made quite a considerable difference to this item. As before stated, the operating costs would have been quite as low as those attained by him. Of course conditions were different in 1915–16; recovery plant no doubt showed by far the best results then. I consider Mr. Fowles has made out an excellent case for the utilization of blast-furnace plant in connection with electricity supply, and those districts which have blast furnaces will be in a fortunate position later on as coal prices increase. I have to call attention to what appears to be a mistake* in the comparison table at the end of the paper. The figure "Capital per kilowatt of plant capacity" is given as £67 for electricity works and only £17 7s. as the average estimated for 50 blast-furnace plants. We all know that it has not cost £67 per kilowatt for plant in electric power supply works, so that it is probable that mains, substations, meters, etc., have been included in the case of the former and not in that of the latter, which spoils the comparison.

[The authors' replies to this discussion will be found on pages 458 and 460 respectively.]

* Since corrected.

North-Eastern Centre, at Newcastle, 22 March, 1920.

Captain A. P. Pyne opened the discussion (his remarks will be found on page 440 of the discussion before the Institution in London).

Mr. J. N. Waite: Mr. Fowles's paper is one that will be welcomed by all who are interested in the generating side of power supply. The paper gives the results obtained from a moderate-sized modern gas-engine power station. As one who is somewhat intimately concerned with the efficiency of both large and small power plants, I welcome the figures given, as they enable a comparison to be made of the results obtainable with gas engines and a modern turbine plant respectively. There is no doubt that for large power schemes the turbine has no rival at present. Although the thermal efficiency of a turbine plant is somewhat lower than that of a gas-engine plant, yet a turbine plant possesses advantages which more than outweigh the difference in thermal efficiencies. This difference is not so great as many of our gas-engine advocates would have us believe. In his introductory remarks the author implies that a steam plant would only realize 30 per cent of the heat realized by a gas-engine plant. I totally disagree with this contention. To be of any use, a comparison between a modern gas-engine plant and a

steam plant should be made on the results obtainable with turbines of modern design. The figures in the paper give for the author's gas-engine station :

Calorific value of gas per cubic foot	98·5 therms
Cubic feet of gas per unit generated	150
Therms per unit generated ..	14,800
Thermal efficiency of station ..	23·1 %

Comparing this with a steam plant to cover similar requirements we will assume that the station comprises three 2,500 kw. turbo-alternators and the necessary modern boilers. To-day, manufacturers are prepared to guarantee for this size of turbine, when equipped for interheating and extensive bleeding for feed-water heating, a steam consumption of 12·5 lb. per kilowatt-hour. This figure is for a station equipped with cooling towers. If the water from a large river was available for condensing purposes this consumption figure would be at least 5 per cent less. With a consumption of 12·5 lb. per unit generated, the heat per unit would be about 16,200 therms. With a boiler efficiency of 80 per cent the total heat expended to produce one unit would be 20,300 therms, and the thermal efficiency of the station would be 16·8 per cent, or 73 per cent of that of the gas-engine station. It may surprise some people, but 80 per cent efficiency can be obtained on modern boilers, and not only obtained but maintained over lengthy periods. If this gas were utilized on a station where large turbine units were installed, then from actual results, and again assuming a boiler efficiency of 80 per cent, a unit could be generated for an expenditure of 16,700 therms, which would give a thermal efficiency of 19·3 per cent, which equals 87·3 per cent of that of the gas-engine plant in the paper. The author when writing the paragraph referred to, must have had in mind some inefficient steam plant of ancient design. As stated previously, if performances of plant are compared, then to be of any practical use the comparison should be made on the results of modern plants for both cases. I notice in the figures given that the crude gas is cooled from 250° C. to 66° C. Assuming a mean specific heat of 0·24, the sensible heat extracted from the gas per cubic foot during the cleaning process is 87 therms, which is almost equal to the total calorific value of the gas presented to the engines. Consideration of this makes it clear that there is considerable scope for improvement from a thermal point of view. The author appears to favour the use of gas engines for the utilization of coke-oven gas. If gas engines are used for this purpose, in what way would the high-temperature inert gases from the ovens be used ? The heat contained in these gases forms a large percentage of the total heat available for power production.

Mr. G. W. Hewson : The blast furnace, besides producing pig iron as its main product, has been described by some as also being a gas producer. It has been ascertained that about half the heat energy of the fuel charged into a blast furnace leaves it again in the so-called "waste gases," and this proportion holds good whether the furnace is working on lean ores with high fuel ratio, or on rich ores with low fuel ratio. Hitherto the bulk of the heat energy of the escaping gases has been utilized upon the auxiliaries of the blast-furnace plant. With modern methods of working the essential auxiliaries of a blast furnace by means of less gas, it is now possible to have surplus gas available for other purposes. This surplus may be anything from 40 to 60 per cent of the total escaping gas. With approximately 300 blast furnaces at work in this country, using say 15 million tons of coke per year, the amount of surplus gas is equivalent to about 7½ million tons of coke, or one thousand million cubic feet of gas per annum, which would be available for generating energy if all were brought up to a moderate standard of efficiency. The question is how far the country is prepared to go in harnessing this large quantity of potential power, which should be utilized from a national as well as private economic point of view. Reference has been made to the working of the stoves on a blast-furnace plant. With dirty gas these could not be raised so high in temperature because of the effect of the alkalies contained in the dust fluxing with the brickwork and materially lowering the melting point of the refractories. With clean gas, however, this danger is removed, and higher heats can be obtained without danger, which in turn results in higher blast temperatures.

Mr. N. W. Prangnell : Without having any experience with the type of plant under discussion, there are a few points I should like to raise with the idea of gaining further information from the large electric power production point of view. The slides shown both by the author and by Captain Pyne seem to take one back at least 20 years, when electric power stations were so attractive to the eye because they contained rows of small-capacity highly polished engines. It would appear that up to the present the total capacity per cylinder for large gas plants is 3,000 h.p. This, in view of present-day requirements for any large capacity output, would necessitate a return to the old type of engine rooms with a number of small capacity engines and costly buildings, etc. As most of the steel-works with their gas-producing plants would be situated in industrial areas, it would certainly appear that they should be taken advantage of by the electric supply authorities, but with steam-driven prime movers and not explosive engines. It would be interesting if data could be produced showing the advantages and increase in efficiency of gas-fired as against coal-fired boilers for steam plants ; also the capital cost and efficiency of the steam-turbine installation of, say, 20,000 kw. capacity as compared with a like capacity of gas engines. It would also be interesting to have figures to show what stand-by plant is considered necessary in these gas-engine plants and what percentage the capital and standing charges represent of the whole charges.

Mr. J. Rosen : Mr. Fowles considers that the production of power from gas furnaces is best obtained by the use of gas engines. Turbines are being used in connection with the waste heat and are very efficient. With gas engines the power-station floor-space is immense and the cost of the operation and upkeep of the units large. The expense of the cleansing and cooling apparatus for the gas is very much larger than if turbines were used. In any case steam plant is necessary to supply the blast engines for furnace blowing referred to on the first page of the paper.

Mr. J. M. Heslop: There are one or two points in the paper on which I must take issue with Mr. Fowles. For example, on page 431 he states that: "The use of gas for boiler-firing is proving a very bad policy, since in comparison with large gas engines only about 30 per cent of the engine efficiency is maintained on the boilers of modern design on clean gas." Let us look more closely into this point. Consider, first, a gas-electric station and take the following figures, which are representative of good modern practice:—

Maximum shaft efficiency	25 %
Average shaft efficiency during operation on good unit load factor ..	21 %
Average generator efficiency	93 %
Average overall efficiency $0{\cdot}21 \times 0{\cdot}93 =$	19·5 %
Allow 8 % for auxiliaries	
Net average overall efficiency $\frac{19{\cdot}5}{1{\cdot}08} =$	18·1 %

Now consider a steam-driven station with modern turbo-generators and again take representative figures:—

Boiler efficiency	70 %
Generator efficiency	93 %
Turbine efficiency	70 %
Available energy (200 lb. per sq. in., 200° F., 28·5 in. vacuum)	398·3 therms
Heat added to steam in boiler ..	1247·4 therms
Overall efficiency $\frac{398{\cdot}3 \times 0{\cdot}7 \times 0{\cdot}7 \times 0{\cdot}93}{1247{\cdot}4} =$ ..	14·6%
Allow 8% for auxiliaries	
Net average overall efficiency $\frac{14{\cdot}6}{1{\cdot}08} =$	13·5%

We have then a net overall efficiency of 18·1 per cent for gas-electric station, and 13·5 per cent for the steam-electric station; or to put the results in slightly different form: the amount of heat converted into useful work in the case of steam plant is $(13{\cdot}5 \div 18{\cdot}1)\ 100 = 75$ per cent of that converted into useful work in the case of gas-electric plant. The author's figure of 30 per cent is therefore open to criticism. Now let us consider a commercial aspect of the case, viz. the effect of the relative capital costs of gas and steam plant on the cost per unit generated. Assume a station of 5,000 kw. capacity operating in conjunction with an existing supply network. In this case, no stand-by plant is necessary and an annual load factor of 80 per cent is feasible. The station output on this load factor will be, in round figures, 35,000,000 units per annum. The gas-electric station would require five 1,000 kw. units which, at the present day, would cost approximately £33,000 each, or a total expenditure of £165,000. If we take the annual charges on this capital at 15 per cent, we have a sum of £24,750, which, spread over a station output of 35 million units, represents 0·17d. per unit. The steam-driven station would have one 5,000-kw. turbo-generator, which to-day would cost approximately £40,000. In view of the lower maintenance charges on modern steam-turbine plant, we can take the annual charges on this capital at 12 per cent, representing a sum of £4,800, which, spread over an output of 35 million units, equals 0·033d. per unit. It will be observed that nothing has been included for boiler plant in the case of the steam-driven station, but, on the other hand, nothing has been included in the case of the gas-electric station for the more expensive gas-cleaning plant required where the gas has to be cleaned to a degree suitable for use direct in gas engines. It would appear, therefore, that a gas-electric station at present is bound to be saddled with very much heavier standing charges per unit sent out than a steam-driven station. Of course it must be admitted that we have by no means reached finality in gas-engine development, in fact, as Captain Pyne emphasized in his remarks, there has been practically no development work done on large gas engines in England for the last five or six years. The figures which I have given above, therefore, represent the situation to-day, but I am by no means prepared to assert that the situation, as between gas engines and steam turbines, would be the same in, say, 10 years' time.

[Mr. Fowles's reply to this discussion will be found on page 460.]

South Midland Centre, at Birmingham, 31 March, 1920.

Mr. F. Forrest: Mr. Patchell states that the first installation put up by him at Messrs. Hoffmann's works consisted of two 360-kw. generating sets which cost £40·98 per kilowatt, or £29,506 altogether. The second installation consisted of four similar sets which were put in at a cost of £50 per kilowatt, or £72,000 for the four sets, making the total expenditure for the generating station £101,506. The average cost per kilowatt of the 2,160 kw. installed therefore amounts to £47 and not £45·49 as given in the table. There is no mention in Table 8 of the cost of water, which must be fairly heavy in the plant, especially as most of it goes through the Paterson's water softener. I should like to ask the author what is the maximum load carried by the generating station, and also what is the maximum demand load factor. The fact that the "Premier" gas engines take about 64 per cent of their full-load consumption when running light or with any load up to half-load, would point to the absolute necessity of always obtaining a very high running-plant load factor. With the variations of the works' load this would point to the necessity of installing a large number of comparatively small sets, which could be started up or shut down as the load varied, in order to maintain the desirable high plant load factor. The installation of six sets seems to indicate that this is just what the author has had in mind. The very low-grade fuel now being efficiently burned by many of the largest generating stations is a type of material which could not be satisfactorily

dealt with in a producer-gas plant of the type described. Much of this fuel is below 9,000 therms per pound, with a large percentage of ash and of fine. Some stations are burning material of this character mixed with gas works' coke-dust and coke-oven dust, and obtaining very good results. Producer-gas firing of boilers mentioned by the author can only be justified if it can be shown that the extra capital cost due to the producer plant, together with the heat losses incurred in operating the plant, are more than offset by the improved boiler-house efficiency, due to gas-firing, plus the revenue derived from the sale of the by-products. With producer gas containing 45 per cent of inert nitrogen, which is likely to give a low flame temperature and with the very heavy cost of storing such lean gas, its use for boiler-firing is not likely to prove a success.

With reference to Mr. Fowles's paper, the utilization of blast-furnace gas which has now been going to waste in many places will undoubtedly receive close attention from those responsible for electric power supply in this country, but it is unlikely that any large proportion of the national power supply will be made dependent upon the utilization of waste heat from any commercial manufacturing process, which is likely to be influenced by strikes of workmen or fluctuations in trade. The production of gas by the blast-furnace plant is a fairly continuous process whilst the furnaces are in operation, whereas the load on an electric generating station will fluctuate between wide limits during the 24 hours. The cost of storing an adequate quantity of heat energy in the shape of blast-furnace gas of only 98 therms per cubit foot would be an extremely expensive matter, and if storage is not resorted to a great deal of gas will continue to be lost.

Mr. W. Wilson : The paper by Mr. Patchell is particularly interesting to me, for I have come into contact in the past with a number of producer plants, very similar to that described, with the sole exception that the recovery of the by-products was not attempted. These plants were situated in a colonial possession and were partly for the supply of electricity to moderate-sized municipalities, and partly for industrial purposes ; and since coming to this country I have frequently wondered why the use of gas was not adopted to a greater extent for electrical generation, especially in view of the large power houses that are operated in the United States by such means. An interesting feature in connection with many of the colonial plants referred to is the use of lignite, which was successfully employed by Mr. Fraser of the Waihi Gold Mining Company as far back as 1907 for the supply of power to what was then the third biggest gold mine in the world. The engines were not quite as large as those mentioned in the paper, the biggest being four-cylinder horizontal Crossley machines, of about 368 h.p. The Crossley design of producer was employed, and the difficulties of gasifying the lignite, which in those days were considered so great as to render its use almost impossible, were overcome with every success. The cleaning apparatus was in the main that described by Mr. Patchell, and reliance was chiefly placed upon sawdust scrubbers, and upon centrifugal extractors, very nearly as described in the paper. Plenty of water was employed in the latter machines, and the serious tar problem was thus effectively coped with. It is interesting to note that the comparative cost of energy by gas and by carefully operated steam engines, employed side by side with the gas engines, was in 1910 about £9 10s. per horse-power per annum for gas, and about £19 10s. for steam. These costs were for continuous working of 24 hours per day, with the exception of Sundays and holidays. Another type of plant, which was successfully developed in this colony, overcame the tar difficulty by means of a locally designed down-draught producer, in which air was admitted to the incandescent fuel at various stages during its descent in the producer, special valves being fitted for the purpose. This enabled the tar to be oxidized and so got rid of without unduly cooling the mass. This method, however, nullifies one of the principal objects that the designer of Mr. Patchell's system had in view, namely, the recovery of the by-products. It may be interesting to mention, nevertheless, that this method had reached such a degree of perfection that small producers were fitted to vessels of the fishing-boat and coastal class for the operation of their existing oil engines. This they did, using the same lignite fuel, without requiring any other cleaning than that afforded by a single washer, consisting of a tank filled with coke through which sea water was allowed to drip. I had the opportunity of witnessing a trial of a small schooner so equipped, in which the original oil engines were driven at their normal speed by such a producer equipment. On page 417 the author mentions that between 2 and 2½ lb. of steam per pound of coal is used for the purpose of keeping the temperature down, and so saving the ammonia. This usually has the effect of increasing the hydrogen content and thereby causing pre-ignition in the engine. I should like to ask the author if this trouble has been met with, and, if so, how it was overcome. On page 418, under the description of the Lymn system, the author mentions that the washing is unassisted by mechanical means. This statement seems not quite accurate in view of the description of the centrifugal cleaners described on page 420 and referred to on page 427. They are the only dynamic cleaners that I have come across in such plants. I have principally given the above details with regard to the gasification of lignite on account of the opinion expressed by the author on page 429 that "it is absolutely certain that low-grade fuel must be better utilized than in the past." It should be mentioned that the lignite to which I have referred was produced at a cost of about 6s. 6d. per ton at the pit's mouth, but cost 16s. per ton at the producers. It will be observed that the examples I have given employed very low-grade fuel (wood has been used in the down-draught pipe of producer) without any extensive complications or additions to the plant. The author has mentioned the shortening of the working week, and expressed a fear that it may have a disturbing effect upon the load factor. The present working week is approximately that to which I have always been accustomed, and it is worth recording that the load factor for the power supply to the City of Christchurch,

New Zealand, was 45 per cent when I last saw the official figures, in October 1915. By paying attention to opportunities for suitable loads, as has been done in this case, the reduction of the working hours should not cause any anxiety.

Mr. H. Bentham: Mr. Patchell has spoilt his paper by trying to compare a one-shift private plant with a public supply undertaking operating under ordinary conditions, much to the disadvantage of the latter. Such comparisons might result in many misleading conclusions. The results shown in Tables 2 and 4 are good, but they are not ordinary working conditions. Load factors of 73·6 per cent (Table 2) and 102 per cent and 84 per cent (Table 4) are not attainable in any plant which operates continuously; they are much too ideal. This plant has undoubtedly been working under the best possible conditions. I think it will be generally agreed that gas plant operating under a steady load and at a high load factor is much more reliable and dependable than when working under other conditions. It would be interesting to know whether the results would be equally satisfactory under fluctuating load conditions. The load factor of most industrial electric supply undertakings is in the neighbourhood of 30 per cent, and if the results given in Table 8 were corrected to this load factor, I estimate the total costs at 1·75d. instead of 0·72d. per unit, a very material difference. Applying a similar revision to the plant under discussion in connection with the Coal Controller's figures (page 428) the thermal efficiency of the gas plant would be 8·15 per cent, a figure somewhat less than that for the steam stations. One must remember that a public supply caters for all classes of load, good and bad, and fits the tariff to suit. Is the local undertaking used as a standby to this plant, or for use in effecting week-end repairs? It would be interesting if the author could give us some idea of the present capital cost of gas plant. I should imagine there is a greater discrepancy between 1920 and 1917 prices than between those for 1916 and 1917.

The fact brought out on page 432 of Mr. Fowles's paper, that practically 3,000 kw. of energy from blast furnaces is going to waste under old methods of working, fully warrants the writing of this paper. There are, however, one or two points which I do not quite grasp, and upon which I should like the author's explanation. He says on page 432 that 450,000 cubic feet of gas per hour is equivalent to about 3,000 units of electricity. This is a thermal efficiency of 22·7 per cent. Is this actually obtained? Also, should not the figure 1,030 million be 1,314 million? If not, how is the 1,030 million units per annum arrived at? I should like to know whether the power used in the rolling mills, shipyards, etc., is taken (1) direct from the gas-driven plant, or (2) from the general supply into which the gas plant is feeding. If the former, what is the behaviour of the gas plant under violent load fluctuations; and if the latter, does the gas plant carry its fair share of the fluctuating load? I am not quite clear about Table 7. Perhaps the author will explain how the figures for "saved in electrical energy" and "extra units of electricity generated" on both sides of the balance sheet are arrived at.

Mr. J. Hargrove: It may be of interest to describe a plant installed about 1912 in North Staffordshire. The plant consists of two high-speed vertical gas engines which use the waste gas from a by-product coke-oven plant, the gas containing a very high percentage of hydrogen. Each engine is designed to develop a full load of 450 b.h.p. and is direct coupled to a three-phase 50-period 2,600-volt alternator. The plant consisting of engines, alternators, foundations, switchboard and half a mile of cable, with pumps, pipework and tar extractor, cost roughly £10,000. Thus, the pre-war running cost, allowing 15 per cent for interest and depreciation, wages for three men, oil and waste, and the manager's salary, is about £2,460. The engines are chiefly used to supply the colliery pumping plant. The number of units generated per week is about 40,000, one engine being used as a stand-by. From the above figures it will be noted that the pre-war cost per unit is approximately 0·28d. Owing to the increase in wages and capital cost of plant for a new installation, the running cost would not be less than 0·8d per unit. No allowance has been made in these figures for buildings, but fuel is included. Great difficulty was experienced originally owing to the high percentage of hydrogen in the gas; and to enable the plant to work satisfactorily on continuous loads it was found necessary to take a proportion of used gas from the silencers through an air cooler to the gas inlet of the engine, which has the effect of reducing the temperature of the flame and prevents the burning of the cylinder heads and explosions in the silencer. On one occasion an explosion in the silencer was sufficiently great to blow off the silencer end, which was carried some 20 to 30 yards. As the fuel for the engine is spare gas from the by-products plant and the running of the gas engine necessitates constant adjustments and attention, it is very questionable whether it is not better policy, especially in connection with a colliery to install well-designed gas-fired water-tube boilers and steam turbines, even at the expense of the efficiency, which is not so important in such a case as reliability, because the steam plant should not require so much skilled attention as was found necessary in the plant described above.

Mr. W. H. Patchell (*in reply, communicated*): The author much appreciates the interest and criticism that his paper has aroused, and regrets that he was unable to accept the invitations of some of the Territorial Centres to attend their meetings. The discussion on the accompanying paper by Mr. Fowles and on his paper was so lengthy as to leave no time for verbal reply; he will therefore endeavour to concentrate on meeting points some of which were made by several speakers and so condense his remarks.

Mr. Taylor and others are confused as to the question of surplus steam. The statement on page 423 that the actual amount of coal for steam-raising is 6·25 per cent of the coal gasified refers to steam for the gas plant as a whole. Table 2 deals with the power plant only. As only 42·7 per cent of the gas at Messrs. Hoffmann's was used for power purposes, the steam generated by the exhaust boilers was not sufficient

to meet the requirements of the gas plant as a whole. Large furnaces may be economically fitted with waste-heat boilers, but the furnaces at Messrs. Hoffmann's are so small as to render such treatment uncommercial. If the whole of the gas plant were required for power purposes then it would be correct to take the figure of 1·7 lb. of coal per kilowatt-hour. In the case of a very large plant, no doubt, the power demands would be such that the figure of 1·51 lb. per kilowatt-hour would be realized. As regards the effect of the sulphate of ammonia recovery on the fuel bill under the conditions and at the prices stated, the net result is the reduction of the cost of fuel by 33 per cent.

The efficiency of a gas plant is an interesting point and somewhat difficult to check, for the reasons stated on page 424. It was impossible to obtain exact figures for the amount of gas made; it is certain, however, that the figures used are very closely approximate, and the average efficiency during the six months covered by the report comes out at 77·6 per cent. Mr. Taylor suggests a figure of 79·3 per cent arrived at in a slightly different way. Messrs. Bone & Wheeler reported on their tests (*Journal of the Iron and Steel Institute*, 1907, vol. 73) from which Mr. Taylor calculates 76 per cent efficiency with 13·25 per cent CO_2.

It is interesting to compare the composition of gas reported on by Mr. Humphrey in his 1897 paper with that quoted on page 424.

	CO_2	O	CO	CH_4	H	N	H_2O
H. A. Humphrey	16%		10%	2·5%	26%	43·8%	1·7%
W. H. Patchell	15·8%	0·15%	10·68%	2·59%	26·6%	44·1%	—

The close agreement is somewhat remarkable, and Mr. Humphrey claims in connection with his tests an efficiency of 81 per cent, so that Mr. Taylor's figure comes between Mr. Humphrey's and the author's.

Mr. Rambush suggests an improvement in efficiency by using the hot water from the jackets of gas engines. This is an interesting field but is not altogether new; the matter was investigated and articles are to be found thereon in *Power* (11 April, 1911, by E. D. Dreyfus and 6 October, 1914, by J. B. Merriam). The effect on the efficiency of a gas engine of varying the temperature of cooling water has been investigated by previous experimenters. The limiting temperature is frequently found to be due to the scale-forming properties of the cooling water and not to the thermal efficiency of the gas engine.

Mr. Woodhouse in his remarks ignores the fact that more steam than that necessary for the proportion of the gas plant used for power purposes is raised by exhaust boilers and tar. Taking his rough figures of 30s. per ton for coal and a recovery of sulphate per ton of coal gasified equal to a net value of 10s., it is clear that the fuel cost is reduced by 33 per cent as stated above. Naturally the respective values of coal, sulphate, and acid, affect the commercial operation of any plant of this kind. Pre-war conditions were certainly more favourable than those now existing.

It is agreed that the load factor has a vital effect and is a most important consideration in the question of gas engines versus steam turbines. The author must not be taken as advocating gas engines in all cases, but with a load factor of over 50 per cent gas engines can be run with a fuel consumption which will compare very favourably with that of steam turbines, and at the same time the important by-product sulphate of ammonia may be recovered. As regards the cost of renewals and repairs, the author agrees that the figures are too high, as he stated in the preamble of the paper. The plant at Messrs. Hoffmann's includes steam engines, suction gas engines and Diesel oil engines, the repairs and overhauling are carried out by the same men, and it is difficult to make an exact division of the items between the old and the new plants. The war conditions contributed very considerably to the item, and the fact that the plant had to run all hours no doubt added considerably to the general cost of repairs. Had close figures been kept of the repairs to the old and the new plant separately, no doubt a more favourable figure could be obtained for the new gas plant. On the question of capital charges and running costs, it is interesting to turn back to the reference which Mr. Leonard Andrews gives in the paper contributed by himself and Mr. Porter (*Journal I.E.E.*, vol. 43). Mr. Fennell suggests that a capital charge of £50 per kilowatt is enormous and not to be considered, but he must remember that the cost of the large steam-turbine station now being built at Birmingham is estimated at over 1½ millions sterling. Mr. Chattock in his evidence at the Local Government Board inquiry is reported to have stated the cost as £44 per kilowatt, as compared with a pre-war price of £15 per kilowatt for the same work.

Mr. Forrest in criticizing Table 8 suggests that the capital charge on the complete plant should have been included. The figures given in that table are not estimates but records obtained during six months' operation of the first plant in 1918. The second portion of the plant was only put into operation in March 1919, as stated in the paper. It is obvious that it would have been improper to include the capital charges on the complete plant or upon more of the first plant than the proportion due to the two gas engines.

Mr. Bentham suggests that the paper describes a plant operating one shift, and compares it with a plant operating under usual public supply conditions. The "one-shift plant" starts on Sunday night and runs through until the following Saturday dinner-time, the power load being subject to the usual meal-time variations. Possibly Mr. Bentham has misunderstood the penultimate paragraph in the paper where it is suggested that the present-day tendencies point to a shortened working week with only one shift worked per day, say 40 operating hours per week. Such conditions would render low-priced power production impossible for either private or public generating stations. It is a very serious consideration, and if coal conservation or thermal efficiency were the only factor it would be very severe on steam stations.

Mr. Wilson is very optimistic and cites Christchurch, New Zealand, as operating at about 45 per cent load factor. Possibly the fact that the power plant there is hydro-electric enables very low rates to be offered, or the local conditions are exceptional. If the municipal owners of plant can suitably arrange hours for pumping, etc., the load factor may be materially affected and improved. However it is done at Christchurch it is interesting, as the Detroit Edison Company with a huge general supply, including railways, only run at from 45 to 50 per cent load factor, based on units sent out of the steam stations.

The progress reported during the war with the Holzwarth gas turbine is very interesting. In the paper referred to by Mr. Lymn (*Zeitschrift des Vereins-deutscher Inginieure*, 28 Feb., 1920) certain curves and tests are given which seem to show a very important advance and a full-load performance nearly as good as that of a reciprocating gas engine, while the curve of total heat used more nearly approaches the "Willans law," with a no-load consumption of about 40 per cent of that at full load.

Mr. Gibbons mentioned that the quantity of lubricating oil used has been halved. He is quite correct. The last four engines put in are lubricated on the Premier Company's standard banjo system. The first two were fitted for forced lubrication and have now been altered to standard. It was found that excessive quantities of oil were drawn out of the crank case into the cylinders by the air supply.

The remarks by Mr. Bass as to the reliability and suitability of the plant are from the user and can be appreciated as such. That the dirty state into which many gas plants are allowed to get is quite unnecessary has been proved at Messrs. Hoffmann's in a way which reflects credit on the staff, who are the first to benefit by it. To keep a plant clean is to diminish the risk of failure and pays as well with a gas plant as with other classes of machinery.

Mr. Chaney's experience is another interesting example of the way that different arrangements of plant may give an economical result. He is right as regards the use of best coal. It has been common where all coal was cheap to use the best instead of lower grades, as frequently the cost of carriage formed an important item in the cost of the fuel and the better grade fuel is so much easier to operate. In spite of Mr. Lymn's reminiscences the author knows nothing better than a fixed grate for burning coal and a mechanical grate for trying to burn "controlled fuel." It certainly is a severe test of the plant and of the operating staff to have to handle as many as nine different classes of fuel in the course of a month and these principally rubbish, but such has been the experience with the plant under review.

Dr. Harker's reference to the Nitrogen Products Committee Report is very appropriate. The amount of work entailed in the preparation of that valuable document was immense. An outstanding point in the Report is the coal consumption given in tons per kilowatt-year, on the basis of 100 per cent load factor, which equals 1·66 lb. per kilowatt-hour for a direct coal-fired steam-turbine plant, and 3·15 lb. per kilowatt-hour for complete gasification. Either figure is improved on by the performance of the plant under review which shows 1·7 lb. per kilowatt-hour actual, or 1·51 lb. if the surplus steam was all beneficially used.

In conclusion the author again thanks the speakers one and all, and also thanks the Council for the mark of their appreciation in awarding him the Ayrton Premium for his paper, which he hopes will be of real service to the members.

Mr. S. H. Fowles (*in reply, communicated*): I am afraid that, judging by Mr. Woodhouse's remarks, he has been very badly informed regarding the working of blast furnaces and their waste gases, and I would refer him to a report by Professor William Bone and Sir Robert Hadfield on "Fuel Economy in the Manufacture of Iron and Steel," read before the Iron and Steel Institute in September last, where, from actual tests, it is stated that 40 per cent of the gas is being wasted. The plant described is at Messrs. Palmers' Shipbuilding and Iron Company and is one of the most up-to-date of its kind in this country. I am sure that a visit from the members of this Institution would be well repaid and be quite a revelation to Mr. Woodhouse. Regarding which are facts and which are statements, if Mr. Woodhouse carefully reads the paper he will notice that it clearly states that the figures are taken over a working year. Professor Bone's and Sir Robert Hadfield's figures were taken as an average of several plants, and to my mind the paper shows very clearly that those figures have been substantiated in practice. Further, it is a fact that we have places in this country to-day where many blast furnaces are blowing gas to the atmosphere at the rate of 400 to 500 thousand cubic feet per hour. This equals about 3,300 kilowatts per furnace per hour. In 1914 there was not one iron and steelworks in this country which was up-to-date, and this is one direction in which Continental engineers were far ahead of us. To my mind it is impossible to become up-to-date by using our surplus gas under boilers until we get a more efficient boiler. The latest guarantee figures for water-tube boilers in December 1919 were as follows: Taking 6,000 kw. units, 250 lb. steam pressure, total temperature 650° F., 28·5 inches vacuum, the guarantee required 202 cubic feet of gas under boilers per kilowatt plus 8 per cent for auxiliaries. This equals 218 cubic feet of gas per kilowatt, i.e. 21,800 therms per kilowatt generated, against 9,000 therms per kilowatt generated on large gas engines and exhaust boilers. Mr. Woodhouse seems to me to have missed the main object of the paper and I must again refer him to the second paragraph on page 431 which reads as follows: "It is for us to look for better methods of using our wasted heat units before attempting to harness any new powers." A little further on the following appears: "and it is to give some rough outline of the better way in which this gas can be and is being used, that this paper is written." This, I think, will answer Mr. Woodhouse's remarks as to whether the paper describes a plant or not. Mr. Woodhouse mentions that it is not possible to use all the blast-furnace gas. I must totally disagree with that statement; the storage of gas would never be taken up on any sized plant. The way to use the waste gas is clearly shown in the

paper, i.e. by supplying the electrical energy by gas engines to a large network and so effecting a national saving. This is actually being done on the Continent and would save this country something like 3,000 million tons of coal per annum. We must remember that the power companies consume 2·5 lb. of coal per unit generated, and yet we waste such a huge amount of gas of potential power and value. Mr. Woodhouse remarked that the case is not so bad as the author would make out. As a matter of fact it is worse than actually stated, and the surplus gas should be something in the neighbourhood of 60 and not 40 per cent. I hope shortly to be able to present figures from actual tests to demonstrate this. In the comparison of boilers and turbines compared with gas engines there is no surplus power from the former, but we have a considerable surplus when using gas engines, the conditions being of course that blast-furnace gas is used. The paper points out that the whole of the furnace blowing, the iron and steelworks, boiler shop and shipyard are supplied from the generating engines running on blast-furnace gas which was originally used on the furnaces themselves, in addition to about 200 tons of coal per week. Now the electrical load on the power station is about 6,000 kw. and is divided up as follows: Steelworks, 3,000 kw.; blast furnaces, 1,000 kw.; shipyard, etc., 2,000 kw. Most blast furnaces are not connected with shipyards and some not even with steelworks, so that in many cases there is evidently 5,000 kw. going to waste or, as stated in the paper, being very inefficiently used. In addition to the load we take or units generated, we could supply the following units to a power company from three blast furnaces:—on 24 hours of an ordinary weekday 70,000 units; and in 360 working days, 25,200,000 units. Assume, for example, that 50 per cent of the ironworks are connected to steelworks; then we must allow the following additional units to be saved:—25,200,000 plus 5,000 units per hour, i.e. 68,040,000 per annum, so that three blast furnaces with steelworks, shipyards, etc., can supply for the greater scheme 25 million units per annum. And three blast furnaces without steelworks, shipyard, etc., can supply for the greater scheme 68 million units per annum, i.e. $\frac{1}{2}(68 + 25) \times 10^6$ or $46\frac{1}{2}$ thousand million units per annum, that is, in excess of the ironmasters' requirements. I think this will clear up the matter of wastage, but it would be very interesting to have Mr. Woodhouse's heat balance-sheet of the blast furnaces where he remarks that they use all their gas on the works.

The general meaning of the paper appears to have been completely overlooked. It seems to have been thought that the paper was intended to compare large gas engines with turbo sets. That is not the case. The intention was to show the most economical and efficient way of using up our waste gas.

Some speakers have mentioned storage of gas. That is quite out of the question. The small townships and company supplies should be compelled to link up, take all the spare energy from such sources, and store the coal. One speaker mentions that if he used coal all the week he would certainly want to use coal and not gas on Sundays. That is not the true spirit in which to look at the matter. It has been mentioned in the paper, and must be borne in mind, that my proposal is in the national interest and not in individual or company interests. Several speakers do not realize the amount of spare gas available. I would refer them to the remarks of Captain Pyne and Mr. Ridge which clearly show what can be done. Other speakers seem to doubt that such a plant exists. To them I would say that we have been operating now for several years and were under the impression that everyone knew of the great wastage.

Mr. Preece mentioned that he did not understand the author's attitude with regard to blast-furnace gas under boilers. There are several reasons against this. I believe I am correct in saying that blast-furnace practice has proved that the turbo blower is not so adaptable for furnace working as a reciprocating blower, owing to the very steady pressure from the former allowing the furnace burden to stiffen up and so cause very bad working. The blower under these conditions is then inclined to churn the air and relax its delivery. The reciprocating blower does keep the burden more on the move and will blow against a tight furnace and build up a pressure until it breaks through the burden. This is one great reason why reciprocating blowers have found great favour amongst the ironmasters of this country, and more so amongst the ironmasters on the Continent. Regarding the efficiencies of boilers and large gas engines, I have already given some recent figures in reply to Mr. Woodhouse. I would refer Mr. Preece to an abstract from a paper on "Recent Progress in the Design of Large Blast Furnace Gas Engines with Special Reference to Belgian Practice," by Professor H. Hubert (Liège University), where some very useful information will be found as to the efficiencies of large gas engines. I would also refer to a paper by Captain C. J. Goodwin before the Society of Chemical Industry (16th July, 1919). Still further information will be found in a Report* by Mr. Cosmo Johns and Mr. Lawrence Ennis to the British Association last September on the fuel economy in the German iron and steel industry. The following figures are given:—

Number of Works	Furnaces in Blast	Gas Driven		
		Blast-furnace Blowing Engines	Converter Blowing Engines	Electric Generators
5	38	64,000 h.p.	34,000 h.p.	86,100 kw.

Steam plants additional in all cases.

This, to my mind, is a very striking case in favour of large gas engines as against boilers fired by gas. Undoubtedly the Germans must have had some great reason for using gas engines, and it is an acknowledged fact that they are much in advance of us in their heat efficiencies. Until we get a more efficient boiler I must hold to the gas engine for efficiency, and that is the vital point to-day, especially where blast furnace or coke-oven gas is being wasted. Another notable fact

* *Engineering*, 1919, vol. 108, p. 428.

connected with all the Continental plants is the adoption of waste-heat boilers on the exhaust range from the gas engines. Some very useful figures are available, which go to show that we are still a very long way from true fuel economy. Something must be done to utilize this great waste and it must be done efficiently. True economy is not always found in first cost. It is my belief and hope that the day is not far distant when the coal to produce the heat units for the manufacture of iron and steel will not be carried beyond the coke ovens, and it will be forbidden to convey coal into any iron and steelworks beyond the coke ovens. I can give one set of figures of iron and steelworks boilers and their consumptions, etc. These figures are from a working test taken during the last 6 months. To generate 746 kw.-hours or 1,000 h.p.-hours on the turbo the following figures were noted :

900,000 cubic feet of gas at 95 therms per cubic foot, 216 lb. of coal at 13,200 therms per lb.

$$\therefore \frac{13{,}200 \times 216 + 900{,}000 \times 95}{1{,}000} = 88{,}451 \text{ therms per b.h.p.-hour}$$

Large gas engines and exhaust boilers are only consuming 7,100 therms per b.h.p.-hour. This will clear up the point of boiler efficiencies against gas-engine efficiencies.

With reference to Mr. Hunter's remarks, the plant described was never clogged up with mud, neither was all the power plant brought to a standstill, but this did happen to the first experimental plant in Germany some 12 years ago. Neither the cost of the plant nor the running cost is higher than that of any other plant ; in fact, they are lower and the plant is more satisfactory in many ways. The electrostatic plant has yet to prove itself for gas-engine working, and the wet plant certainly saturates the gas to its full limit. Therefore I consider that the Halberg-Beth is so far the most suitable for engine working. Moreover, I am very doubtful whether the sensible heat mentioned by Mr. Hunter holds good when the gas has a long distance to travel to and from the cleaning plant. The competition which we have to face will certainly compel sooner or later all blast-furnace people to install large gas engines on the grounds of efficiency. Therefore the most suitable plant will be the one that caters for them, and that is certainly not a cold wet or a dry hot process. The quantity and quality of the gas does not vary as indicated by Mr. Hunter, and I am convinced that if he could visit a modern plant it would be a revelation to him. The last paragraph of Mr. Hunter's contribution is valuable, and to some extent bears out my remarks on page 431 of the paper where it is stated that under the old conditions coal had to be used in addition to all the gas that was made. It certainly gives us a very good idea of the very inefficient way in which many blast-furnace plants are being run even to-day. The plant described is run entirely on blast-furnace gas, the boilers are absolutely cut off, and the whole of the blast-furnace blowing and power, steelworks, boiler-shop, engine-works, and galvanizing works are kept fully supplied with electrical power, water and air, from the gas-driven engines, and some 80 to 100 thousand B.O.T. units per week are generated in excess of our requirements. This may be useful data to Mr. Hunter and I would say that any blast-furnace plant that cannot maintain this proportion of load is certainly not up-to-date. It is well known that this is never done when the gas is used under boilers of the most modern design.

Any maker of large gas engines would give Mr. Bentham a guarantee of 10,000 therms per brake horse-power down to well below $\frac{3}{4}$ load ; that is equal to 150 cubic feet, at 100 therms per cubic foot per kilowatt-hour. The figure of 1,030 million units is obtained thus : 20,610,200 × 50 = 1,030 million units per annum from 50 blast-furnace plants of three furnaces each in blast. As a matter of fact, that is only just 50 per cent of the furnaces in blast and is given as a very moderate estimate. Regarding the power supply, the paper states that we run in parallel with a public supply company, so this power is taken from the common source. We have, however, run isolated and were not disturbed by the most violent swings on a large steelworks motor of several thousand horse-power. The gas-engine plant whether isolated or in parallel always takes its fair share of the peaks. The items saved on electricity are explained as follows :—

£88,540. This was previously bought.
£35,425. This is due to an extension, and would be the cost if the units had to be bought from the above source.

$$\therefore £88{,}540 + £35{,}425 = £123{,}965.$$

The cost of that number of units on the new method = £24,791, so that £123,965 − £24,791 = £99,174 saved on the total units generated.

Mr. Hargrove points out that he paid £10,000 for 680 kw. That figure is very high for pre-war conditions. It is possible for one man to attend to 2,000 kw. of gas-engine plant and this is being done to-day. This considerably reduces the cost per unit generated, and our figures to-day nowhere approach Mr. Hargrove's pre-war cost per unit generated. I agree with Mr. Hargrove that coke-oven gas is not so easy to deal with and I would refer him to page 435 of the paper, where the subject is dealt with. With blast-furnace gas so clean and free from tar, and so low in value and constant, it is criminal to use it in any other way for power than in large gas engines.

In reply to Mr. Waite, the latest figures taken at the time of writing the paper and given by Mr. D. Wilson, Technical Adviser to the Controller of Coal Mines, show that the best power station in Northumberland was consuming 1·8 lb. of coal per unit generated and had a thermal efficiency of 18 per cent. Now at 11,000 therms per lb. this equals 19,800 therms per kilowatt generated, against some large gas engines and exhaust boilers which are now coming out well under 10,600 therms per kilowatt on blast-furnace gas. Now if we take the average of stations in the same district and Mr. Wilson's 2·40 lb. of coal per unit generated, and assume 11,000 therms per lb. again, we get 26,300 therms against 10,000 on our large gas engines and exhaust boilers. It must be remembered that this

2·4 lb. of coal is on modern large-sized water-tube boilers, so the figures I quoted of 20 per cent efficiency on blast-furnace boilers compared with gas engines can well be understood.

With reference to Mr. Rosen's remarks, I must repeat that the paper was not written to compare gas engines with large turbines. For waste gas I must maintain that the gas engine is the best proposition. The floor space occupied per kilowatt of gas engine is very little more than that of boilers and turbines even in the latest stations. Steam plant is not required to supply the blast for the furnaces, this being done by large gas-engine blowers (see page 433). The steam engines were used only under the old conditions.

I think Mr. Heslop has quoted a very modern steam station, but I would refer him to my reply to Mr. Waite. I would quote a very modern plant where water-tube boilers have been installed and work under the following conditions: Gas made = 3·0 million cubic feet per hour from three furnaces; gas lost at bleeders = 0·5 million cubic feet per hour; gas used on boilers and stoves = 2·5 million cubic feet per hour for furnaces only; boiler efficiencies = 60 per cent. In this case, therefore, they have no gas to spare for other purposes. I think this will prove the point for gas engines and the efficiency that can be obtained, also the wasteful manner in which the gas is being used on the plants generally installed in iron and steelworks. This will serve to answer more fully some of the speakers' remarks in the Middlesbrough discussion and also Mr. Hunter.

Mr. Coulson says that there has not been an adequate return on the gas-cleaning plant. I think the balance sheet shows the return quite clearly to be on the side of cleaning all the gas thoroughly. I would also refer him to Captain Pyne's and Mr. Ridge's remarks.

In reply to Mr. Hobson, the seven gas engines were installed to cope with an extension in the works. We find 15 per cent to be ample stand-by. The therms are taken at 10,000 per brake horse-power on full load, the small variations being put in to show the progress. The 40 per cent of cleaned gas for stoves is to allow a liberal margin for all makes of stoves. We are now getting results down to 32 per cent and hope to reduce this figure in future. The total number of continuous running hours on a gas-engine generator has been 1,200 at 95 per cent of normal full load.

With reference to Mr. Marshall's remarks, coal is not used on the boilers for the rolling mills. The complete rolling is now done electrically from the power station. The load curve includes all the yard load of the various departments, as previously mentioned in my reply, with the exception of the extension which has lately been put into commission.

The 0·15 million cubic feet of gas used per furnace was given as a liberal estimate and, as stated in the paper, is an approximate figure for one furnace on the new method. I agree with Dr. Morley that it is high.

Captain Pyne has pointed out some very long periods of gas-engine running and this can be upheld from our practice in this country. It will, I think, remove many doubts. I must thank Captain Pyne, Mr. Pilling, Dr. Morley and Mr. Ridge for their valuable contributions to the discussion. Mr. Ridge asks for an explanation of the 8·3 per cent oxygen in the exhaust gas. This was found afterwards to be due to an air leak in the main where the exhaust gases were tested.

THE ELECTRICAL EQUIPMENT OF ARTISAN DWELLINGS.

By LEONARD MILNE, Member.

(*Paper first received* 20 *January, and in final form* 4 *March*, 1920; *read before* THE INSTITUTION, 25 *March, before the* DUNDEE SUB-CENTRE, 30 *April, and before the* NORTH MIDLAND CENTRE, 11 *May*, 1920.)

The electricity supply to artisan dwellings which are projected and in course of erection under the Government Housing Scheme, is a matter of much interest to many electrical engineers, for, although the consumption in each house will probably be very small, the number of houses about to be built is so great that, in the aggregate, these dwellings may use many millions of units in the year.

If electricity is to be employed in this class of house for lighting and other purposes, it would appear essential that the installation costs should be very much reduced from those to which we are now beginning to become accustomed.

The argument has been put forward that, since the present cost of building is so great, and the cost of an electrical installation such a small percentage of the total figure, economies in installation costs are of small importance.

This argument appears to me to be entirely fallacious. It is human nature and, in my business experience, I have always found that when the cost of any work is less than is anticipated, a purchaser is ready to spend money, but that when the cost of work is higher than the preliminary estimates, a purchaser will seek to economize in every direction. Thus, the greater the cost of present-day building work, the more important it becomes to economize in such services as water and electricity supply.

Dealing first with an installation for the supply of lighting only to an artisan dwelling, I find from examination of various plans that, on the average, the house contemplated would require 9 lighting points, and I have had estimates prepared for the internal installation work on various methods at present in vogue, with the following result* :—

Cost of 9-light installation in screwed enamelled welded tube with 600-megohm grade C.M.A. cable of sizes conforming to the requirements of the Institution, including main switch and main fuses, distribution board, plain fittings, lamps and switches	£19 13s. 8d.
The same in close-joint conduit with continuity fittings	£14 1s. 0d.
The same in wood casing	£16 3s. 0d.
The same with wires carried on porcelain cleats and unprotected except where they rise through floors and pass through walls	£11 4s. 8d.

* All estimates in this paper are based on the prices ruling in the autumn of 1919 and the sizes of wires then in common use. Increases in the cost of labour and material and recent variations in the sizes of wires do not, however, materially alter the comparative figures.

Examining the points where it would seem possible to effect a saving, I would first suggest that a main switch in these small dwellings, when lighting only is provided, could quite well be eliminated, substituting therefor two replacement fuses. A small main switch is very rarely used, and if at any time one wants to use it one will find, in nine cases out of ten, that it is so corroded and jammed with dust and dirt that one can neither pull it off nor put it on without breaking it. If we rely on a replacement fuse we can pull it out with certainty; and if we try to put it in, even with all lights on, no harm will happen on such a small installation.

From examination of the estimates previously given, I am of opinion that some form of uncased cleat wiring must be used, on the grounds of economy.

A very large amount of work was carried out on this system for the War Office during the war and the late Colonel Seaman, then Chief Electrical Engineer of the War Office, informed me that, although he had seen much of such work carried out in the worst possible manner, he had never traced any fire or accident happening therefrom.

With regard to the wires themselves, it appears quite unnecessary to use such costly material as 600-megohm grade cable on the neutral side of those systems where one pole is directly and permanently connected to earth, since at the outside we could only be dealing with differences of pressure of a very few volts between this conductor and earth. The insulation of the braiding of the wire and of the porcelain cleat would, I submit, be amply sufficient for the neutral side.

It may be suggested that, in the case of a fault developing between the outer and neutral of a three-wire system of distribution, the pressure between the neutral and earth at certain points may rise sufficiently to involve an appreciable fire risk in the event of a neutral wire, protected by braiding only, being accidentally brought near to or touching an earthed conductor. This suggestion is contrary to experience.

Those who have had occasion to change over the poles of an old installation on a three-wire system and have noted how frequently it happens that on doing so the fuses are at once blown, will agree that there are to-day an enormous number of installations in which the insulation on the neutral side is practically nil, and yet I cannot find any case in which it has been observed that the occurrence of a fire was coincident with the development of a fault between the outer and neutral on the system.

As to the size of wire employed, at the present time a No. 18 S.W.G. is the smallest wire permitted by the

Wiring Rules. The considerations on which this Rule is based are undoubtedly mechanical, not electrical.

I would suggest that, in the case of twin wires, the minimum size permitted should be reduced from No. 18 to No. 20 S.W.G., since the mechanical strength of a twin 20 S.W.G. wire is at least equal to the mechanical strength of a single 18 S.W.G. A twin wire might be used, made up with one core of No. 20 S.W.G. insulated to 600-megohm grade with a bare No. 20 S.W.G. laid in long spirals around this, and the whole braided over all.

Such a twin conductor, compared with two separate conductors of No. 18 gauge, effects a saving of 50 per cent in the cost of wire.

In such a building as we are considering, a No. 20 S.W.G. conductor is amply large enough to carry all the lights required at a pressure not less than 200 volts.

The saving due to the employment of twin wires is, with short runs, more than lost in labour and waste of material where switch drops are brought down to hand-level. Where the switch branch leaves the main run the wires must be cut and rejointed, and between this point and the switch one core is wasted.

I would therefore propose to dispense with switch drops, to place a combined switch and ceiling rose (or a switch and ceiling rose mounted together on the same block) on the wall near the ceiling level, and to operate the switch by a cord or rod attachment. The position of the combined switch and ceiling rose can generally be chosen so as to be close to the door of the room.

From this ceiling rose I would run a twin flexible wire, passed over an insulated hook, directly to the point where light is required. This twin flexible I would again construct of one insulated wire and one semi-insulated wire. In this way a saving of 40 per cent would be effected in the cost of flexible cords.

Incidentally, the arrangement proposed has the advantage of practically insuring branch switches being placed on the live side of the system—a point which I have frequently found neglected on otherwise well-executed installations.

Another incidental advantage is from the point of view of appearance. A single wire run on single-way porcelain cleats is much less conspicuous and of better appearance than the usual two or three wires run side by side on two- or three-way cleats.

Where conductors run of necessity through floors, they should be protected up to the skirting level or possibly above hand reach, preferably in $\frac{3}{8}$ in. insulating tube. They should also be protected in a similar manner where passing through walls. Such protection, primarily mechanical, would, with the braiding, provide for the otherwise bare conductor sufficient insulation to prevent electrolytic action.

The total result of the economies suggested is that the cost of a 9-light installation as described would amount to £7, as against a sum varying from £19 13s. 8d. to £11 4s. 8d. for the cost of a similar installation on the recognized methods before referred to.

In each case my estimates are based upon the perhaps somewhat haphazard methods at present in vogue, in which there is practically no co-operation between the architect, the builder, and the electrician. The usual custom is for the bricklayer to build his walls, the plasterer to render them carefully, and, when all this is nicely done, for the electrician to come along and cut away. This may be, in the long run, the cheapest way of proceeding when we are dealing with one large building; but when we are dealing with small buildings, the design of which is exactly repeated hundreds and thousands of times, I hope that we shall see closer co-operation between the architect, the builder, and the electrician, so that wood fixing blocks will be built in at all positions where fixings are required, and that passage ways will be left where necessary in all walls and ceilings. These fixings can be provided practically without additional cost as the building proceeds, whilst the labour of cutting away, and making good, amounts to approximately one-third of the total labour on the installation.

The revenue from lighting only at, say, 6d. a unit, would probably not amount to more than £2 to £3 per annum from each house. The cost of a separate service, service fuses and meter, for each house would probably amount to not less than £8. Allowing 10 per cent for interest and depreciation on services and meters, these charges would amount to roughly one-third of the expected revenue. It is therefore of importance that the capital cost of services be materially reduced.

Doubtless one service would be arranged for a group of houses, and I would suggest that the supply from house to house of the group should be made by means of bare overhead wires carried on insulators attached to the chimneys of the buildings, and that the supply should enter at the top of the house and not at the bottom, the supply authority's apparatus being fixed on the upper floor instead of on the lower floor. This arrangement has the further advantage of providing the driest position for fixing the supply authority's apparatus.

A meter for each separate consumer is a heavy charge for the anticipated revenue, and where lighting only is installed consumers might be charged a fixed annual rate and a meter eliminated.

The objections to such a fixed charge under a contract for lighting only is that it leads to extravagant consumption and to the dishonest use of lighting points for electric kettles, irons, and all the various appliances which can be utilized with a lamp-socket adapter; or, on the other hand, to the use of electricity for domestic purposes other than lighting being hampered.

I have tried the method in two small agricultural towns of a very similar size and character, with results varying in a remarkable way. In the one case the annual consumption worked out on the average to 31 units per 40-watt lamp installed. In the other case, the annual consumption worked out at 46 units per lamp installed, and this method of charging had to be abandoned. On investigation, it was found that there were a very large number of kettles, irons, etc., used in the town, the current for which was not paid for; and, in fact, as a method of promoting the sale of domestic appliances I would commend this system of charging for the consideration of the Electrical Development Association. I would hazard a guess

that there were more electric irons and heaters sold per head of population in the town in question than in any other town in the United Kingdom.

I think that for houses built under the Housing Scheme, which will to a large extent be of exactly the same size and type, the difficulty of improper use of current supplied under a contract for lighting only could be met by installing one meter for, say, every dozen or 20 houses, charging a fixed rental sufficient to cover the most extravagant use of current for lighting purposes, and allowing a quarterly rebate to each consumer when the meter reading showed a consumption below the predetermined estimated figure. By this means, it would be to the interest of each consumer to economize, and the improper use of current for purposes not included in the contract would probably be at once notified and stopped. The other objection, that development is hampered, still remains.

It is highly desirable that a supply of electricity should be available for all purposes—for heating, for cooking, house cleaning and washing, and for small power for labour-saving devices. For a general supply a separate meter for each house appears to be essential, but the anticipated revenue would be sufficient to justify this expenditure.

To avoid installing two meters, one for lighting and one for power, the system of charging a fixed annual sum plus a small charge per unit used for any purpose has distinct advantages. The ideal system, which should be free from complication, easily understood by the consumer, adapted to promote the general use of electricity for all purposes, and equitable, has, I think, still to be found.

As regards heating, I do not think we can anticipate the elimination of fires from the room, or rooms, where heat is constantly required. Our British prejudices call for a fire that we can poke and, although an open coal fire is undoubtedly wasteful, it is at all events a very healthy form of waste in the living room, as it ensures proper ventilation.

In bedrooms, where artificial heat is only required in case of sickness and on rare occasions, electric stoves are eminently suitable.

The suggestion has been made that considerable economies in building would be effected by completely dispensing with chimneys and grates; and, with the one exception of the main living room, I think this could be done with great advantage.

I am informed that the saving in cost of building by dispensing with chimneys and grates in all rooms but the living room, and by substituting for them efficient forms of ventilation, would amount to approximately £25 per house and would further provide an additional 15 square feet of available floor-space.

The cost of wiring with twin wires as previously described for the heating plug in each room from which a fireplace has been removed would only amount to approximately 18s. per point, or £4 10s. for the house with five power points. I have not included in this figure the cost of the electric stoves themselves, for it seems quite unnecessary that these should be provided by the landlord for each room in each house. Electric stoves, and other electrical apparatus which are only occasionally used, should be available on the estate for hire by the tenants.

With regard to electrical cooking, by reason of the complete control and lower average temperature required, the resultant saving in food wastage alone should cause the adoption of electrical cooking on grounds of economy.

There are on the market several satisfactory kitchen outfits suitable for a working-class family, and the cost of such an outfit, consisting of an electric oven 18 in. × 15 in. × 15 in. with four controls, boiling plate 18 in. × 10 in. with three controls, a grill 9 in. × 8 in. and a two-pint kettle, would amount to about £14 at present prices, and the daily consumption for cooking for a family of five would average about 7½ units. In the United States the average figure is stated to be under 1 unit per day per person.

It will pay the electricity supply undertaking to quote preferential rates for cooking in an artisan dwelling, since the range will be used chiefly for the midday dinner at or near the time of minimum day-time load on the station.

The stumbling block to electrical cooking, however, is the question of domestic hot-water supply. In the majority of cases a domestic hot-water supply is inadequately provided from a saddle-back boiler in the kitchen fire. This is not satisfactory, as hot water is only available when there is a large kitchen fire, or it is very uneconomical if a large fire is kept up for the sole purpose of providing hot water.

The alternative, of using a separate stove burning anthracite, is more convenient and more economical than keeping a kitchen fire alight to provide hot water; but this method is perhaps still too expensive for the artisan dwellings under consideration.

An adequate supply of hot water from an anthracite stove for a family of five persons will require, approximately, an average consumption of 22½ lb. of anthracite per day. Taking anthracite as costing at the present time £3 5s. a ton, the daily cost amounts to approximately 7¾d. Roughly, this will provide the equivalent of 50 gallons of hot water at a temperature of 104° F.

Better results could undoubtedly be obtained by lagging the usual hot-water cistern and supply pipes. With the present crude form of unlagged cisterns and unlagged pipes, the heat losses over a period of 24 hours amount to an average of approximately 70 per cent of the total heat units put into the hot water This calculation is based on the losses from a cubic cistern containing 20 gallons and 30 ft. of 1 in. hot-water pipe at a temperature of 130° F. and surrounding atmosphere and inflowing water at 55° F.

Another alternative is to obtain the hot-water supply from a gas-heated geyser. To obtain the same quantity of hot water at the same temperature, namely, 50 gallons at 104° F. raised from 55° F., would, according to figures given by manufacturers of geysers, require a consumption of 75 cubic feet of gas, to which must be added, if the arrangement is to be convenient, the amount consumed by a pilot burner, which would be alight for, say, 12 hours a day and consume 5 or 6 cubic feet per hour, making the total gas consumption 135 cubic feet per day. Taking the price of gas as

4s. 6d. the cost would be, say, 7¼d. per day. To obtain a sufficiently rapid supply of hot water from a gas geyser, it is essential that the gas pipes in the house should be of large size. In existing dwellings sufficiently large gas pipes are rarely found, and to install them in new houses involves considerable capital outlay.

The question of the electrical heating of water for domestic supply merits, I think, more investigation and consideration than it has yet received.

There are several electric water-heaters on the market for which an efficiency of 90 per cent or over is claimed when the apparatus is used to its full capacity over a period of 24 hours, and I am of opinion that such an efficiency should be obtainable. A still higher degree of efficiency could doubtless be obtained without thermal storage, but it appears essential that some form of thermal storage be employed if electric heating of water is adopted.

To give a convenient supply of bath water, 18 gallons of water at a temperature of 104° F. should be available within 10 minutes; and to provide this without thermal storage, even with a heater of 100 per cent efficiency and assuming a temperature of 55° F. for the inflowing cold water, would require over 15 kw. for 10 minutes. Such a load is not one that supply engineers would be prepared to take on at the low price which is essential if the electrical heating of water for domestic purposes is to come into general use. With thermal storage, and a load factor of practically 100 per cent, a supply is even to-day obtainable at 1d. a unit; and with arrangements which would ensure that the water-heater load was off at times of peak load, I should anticipate that a rate of ¾d. per unit or less would be quoted.

Adopting the same figures for the adequate supply of water to a small house, namely, 50 gallons at a temperature of 104° F., and taking an efficiency of 90 per cent, the cost at ¾d. a unit works out at just over 6d. a day.

The forms of water heaters with thermal storage with which I am acquainted involve storage of heat either in the water itself or in a mass of cast iron raised to a comparatively high temperature, about 600° F.

The objections to thermal storage by means of the heated cast-iron block are the weight and bulkiness of the apparatus.

The objection to thermal storage in the hot water itself is that either a large cistern is required for adequate storage, or that the water has to be stored at a high temperature, increasing the thermal losses and, moreover, rendering the water unpotable and liable to deposit scale. A temperature of about 130° F., which is hot enough to shift grease and will not "stew" the water, is usually adopted.

It is desirable that water at a boiling temperature should be available in small quantities, a somewhat larger quantity at about 130° F., and a copious supply at 104° F.

Although a domestic hot-water supply may be obtained more cheaply electrically than in any other way—6d. as against 7d. to 8d. a day—the price is still somewhat high for an artisan family. I am inclined to think that the direction in which the final solution of the problem lies is to fit a small boiler in the parlour grate, to store tepid water at, say, 80° F. or 90° F. in winter time, and to employ what may be called an electro-thermic booster to raise the tepid water to the required temperature.

At 80° F. to 90° F. the radiation losses are small, and lagging of the cistern will be of minor importance.

In summer time when there is no parlour fire, a little more electric power will be necessary; this, combined with arrangements ensuring that the peak load is not overlapped, gives a most desirable load to the supply station.

A further investigation on the subject of thermal storage is urgently called for. Possibly good results might be obtained by making use for thermal storage of the latent heat of fusion of some metal, alloy or salt such as nitrate of soda, or the latent heat of crystallization of the solution of a salt, such as acetate of soda, which has already been used for thermal storage.

I have dealt with this subject at some length, not only on account of its intrinsic importance from a hygienic point of view, but also because I believe it to be the key to the extensive introduction of electric cooking. Solve the domestic hot-water problem and electric cooking will necessarily follow.

From figures previously given, it will be seen that, leaving out of consideration on both sides of the account the provision of a hot-water supply, the capital cost of the complete electrical equipment of an artisan's dwelling, including cooking apparatus, is practically covered by the saving on the building due to dispensing with chimneys and grates.

I will not attempt to enumerate the various other labour-saving devices which are on the market, and which will be extensively used in the artisan's house when a cheap electricity supply is available in every room, but I would call attention to one piece of apparatus which should be and, as far as I know, is not on the market, namely, an electrically heated airing cupboard. Most small houses are at present very inadequately provided with airing facilities, and there is generally no alternative to the unhygienic method of drying garments before the fire in the living room.

An electrically heated airing cupboard, properly ventilated to the outside, is an inexpensive convenience which will do much to promote the health of the people.

In conclusion, there is one point to which I would refer. The introduction of steam was the cause of the decay of almost all our cottage industries; I believe that the introduction and wide distribution of cheap electrical power in artisans' dwellings may to a large extent revivify cottage industries.

There are undoubtedly a large number of processes, where the weight of goods to be handled is small, which can be as well and as cheaply produced in the cottage as in the factory, and I believe that the coming generation will see our women and elder children again working in their homes instead of crowding to the factory, to the great social advantage of the community.

[The discussion on this paper will be found on page 476.]

EARTHING:

REPORT OF THE EARTHING SUB-COMMITTEE* OF THE WIRING RULES COMMITTEE.

(*Report received 8 July, 1919, and discussed at a meeting of* The Institution, *25 March, 1920.*)

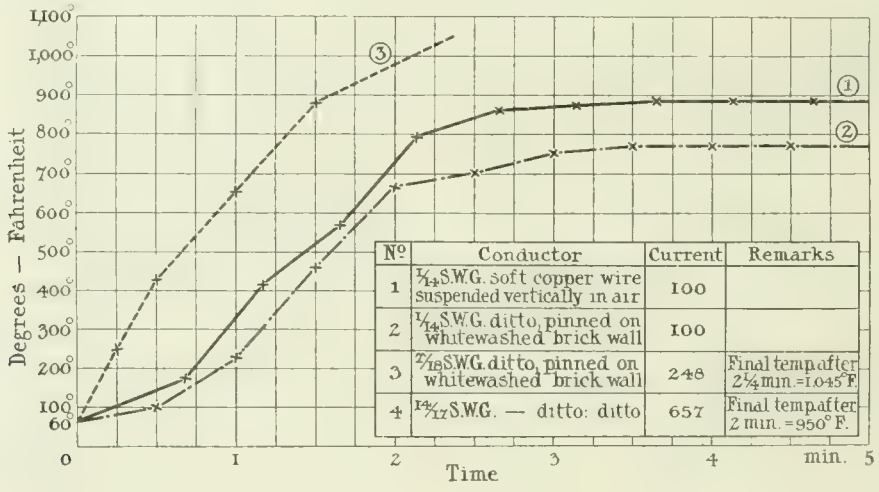
The Sub-Committee were asked to ' consider the whole question of earthing (including the time element of circuit-breakers, the heating of conductors, the current-carrying capacity of the apparatus earthed, the drop of pressure in metal sheathing, and the number of earth wires required)."

In accordance with these instructions the Sub-Committee first proceeded to determine experimentally the heating of earth wires, i.e. bare conductors of various cross-sectional areas, having in mind that Rule 34 in the Seventh Edition of the I.E.E. Wiring Rules requires one No. 14 S.W.G. wire, or conductor of an equivalent cross-sectional area, to be provided for every 50 amperes or part thereof of working current, and that Rule 98 (*b*) allows the use of a fuse which will permanently carry any current less than three times the normal for working currents not exceeding 10 amperes, and twice the working current for larger conductors. Fig. 1 shows the rise in temperature for bare conductors of various sizes carrying twice the working current allowed by the Institution Rule for the corresponding cross-sectional area of insulated conductor, i.e. the current which an earth wire may have to carry indefinitely under the present Rules.

It will be observed that the temperatures arrived at are much higher than will be considered safe. Thus, a No. 14 wire reaches a temperature of nearly 900° F. from an atmospheric temperature of 60° F., and a 7/18 S.W.G. stranded conductor 1,045° F., in 3 minutes from the application of the current, and are visibly red hot. This confirms the results anticipated by Mr. G. S. Ram in a letter (12 March, 1918) to the Secretary of the Institution.

The considerable cooling effect obtained by attaching a wire to a brick wall will be noted, but the Sub-Committee do not consider it safe to calculate the sizes of earth wires for a given current, except on the assumption that the wires will be entirely surrounded by still air.

It was considered that an earth wire should be so designed in size that, assuming the correct operation of the fuse, the temperature could never rise to that of the melting point of tinman's solder, i.e. about 392° F.,



No.	Conductor	Current	Remarks
1	1/14 S.W.G. soft copper wire suspended vertically in air	100	
2	1/14 S.W.G. ditto, pinned on whitewashed brick wall	100	
3	7/18 S.W.G. ditto, pinned on whitewashed brick wall	248	Final temp. after 2¼ min. = 1045° F.
4	14/17 S.W.G. — ditto: ditto	657	Final temp. after 2 min. = 950° F.

Fig. 1.—Curves showing temperature rise of bare, soft copper conductors.

in order to ensure the permanency of the connections and to avoid fire risk. It has to be kept in mind that, apart from the question of danger to life, the whole object of an earth wire is to enable the fuse to open the circuit.

Now the size of a conductor necessary to fulfil this condition is obviously determined by the maximum current that may flow, and by the time during which it flows, if the interval of time is anything less than that necessary to raise the conductor to its maximum temperature at the given current.

The Institution Rule dealing with fuses, No. 98 (*b*), states :—

" They must effectually interrupt the current when a short-circuit occurs, and they must be so propor-

* The Sub-Committee consisted of Mr. G. S. Ram (Chairman), Mr. J. Frith, Mr. G. H. Nisbett, and Mr. A. L. Taylor.

tioned to the current to be carried that no conductor protected by them can be raised in temperature above that specified in Rule 44. When the working current (Table, Cols. 3 and 4) does not exceed 10 amperes, the fuses must be proportioned to interrupt the current before or when the current through the conductors rises to 3 times the working current; for working currents above 10 amperes the fuses must be proportioned to interrupt the circuit before or when the current through the conductor rises to twice the working current. The use of fuses of the enclosed type is recommended, and in any case fuse wires must be individually protected. No fuse smaller than one having a working capacity of 3 amperes, to fuse at 9 amperes, need be inserted for final sub-circuits."

It will be noted that no time limit is specified; it therefore follows that a fuse that will permanently carry, say, 299 per cent or 199 per cent of the working current (depending upon the size of conductor) will comply with the Institution Rule provided it opens the circuit at respectively 3 times or twice the working current.

It became obvious to the Sub-Committee that a fuse designed for the limits allowed by the Institution Rules would permit of a serious overheating of the conductors if we are correct in assuming that the "maximum current permissible" given in Column 3 of the Wiring Rules Table refers to the working load of the cables, as would appear from the context.

Using the formula of Messrs. Melsom & Booth on which we believe the allowable carrying capacities have been calculated (Rule 43), it is seen that those conductors on which less than 3 times the working load is allowed might reach in from 3 to 10 hours, depending on the size, and with an atmospheric temperature of 100° F., a total temperature of over 200° F. for rubber-insulated cables and of over 210° F. for fibre-insulated cables. Those sizes on which an overload of anything less than twice the working current is allowed would similarly reach a total temperature of over 180° F. for rubber, and about 300° F. for fibre cables.

The limiting conductor temperatures are laid down in Rule 44 as 130° F. for rubber and 176° F. for fibre, and it therefore follows that:—

(1) The allowable temperatures must be increased, or
(2) The working current must be reduced, or
(3) The margin of overload for fuses must be lessened

Taking these in order:—

(1) We are of opinion that it is not advisable to raise the allowable maximum temperatures for rubber- or paper-insulated cables.

(2) It is undesirable on economic grounds to lessen the allowable working current on the conductors if it can be avoided, but as a help towards meeting the difficulty we suggest that the Rules should be altered so that the allowable working current stated in the Appendix to the Rules (cols. 3 and 4) should be based on a maximum atmospheric temperature of 80° F. instead of 100° F. as at present.

Higher temperatures than 80° F. are seldom met with in ordinary practice, and a note of warning that lesser working currents must be used for higher atmospheric temperatures would sufficiently cover exceptional cases.

If, therefore, this were done, seeing that the carrying capacities in the Wiring Rules Table have been calculated for a rise in temperature of 20 degrees F. in the case of rubber cables, and 50 degrees F. in the case of paper cables, we should then have for the operation of the fuse a margin between the working temperature and the maximum allowable of, in the case of rubber cables 30 degrees F., and for fibre 46 degrees F., instead of at present only 10 degrees F. for rubber cables and 26 degrees F. for fibre cables.

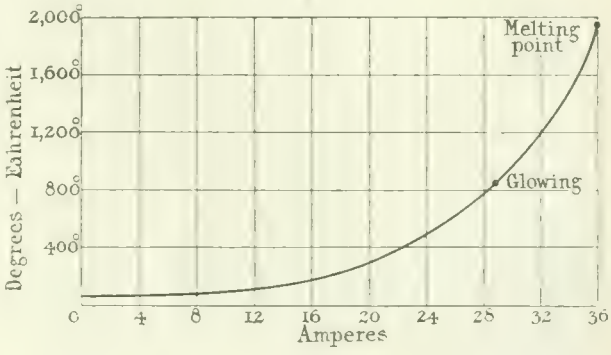


FIG. 2.—Curve showing temperature of tinned copper-wire fuse (3 in. break; open type) with various currents.

(3) Coming to the third possibility, namely, the reduction of the overload to be allowed by the fuse, the ideal fuse from the point of view of permitting the maximum working load on the conductors, with a given limitation of temperature rise on the cables under all circumstances of overload, would be one that interrupted the circuit with the minimum excess current over the load it would carry with stability; and it is necessary that, for the reasons already stated, we should have a fuse that will act within the limits of temperature stated in par. 2.

Copper fuses as now commonly used are unsuitable for the purpose we have in mind, as the margin between the safe working load and the fusing current is a wide one compared with other metals available. Fig. 2 shows the temperature curve for a typical copper-wire fuse, from which it will be seen that if such a fuse is to open the circuit at all with an overload of, say, 50 per cent, it would be so hot (500° F.) at the working load that it would be in a state of instability and would, owing to oxidization, ultimately open the circuit when it was not required to do so. Moreover, a copper fuse

set to these limits would not comply with the Institution Rule 98 (*a*) reading :—

"No over-heating of any part must take place when the full current flows continuously."

This rule the Sub-Committee think should be maintained.

to the flow of the metal. A lead and tin mixture is better in these respects, but it is impossible to ensure a constant composition, and as the fusing current varies considerably with small changes in the percentages of the metals, it is necessary that each fuse should be separately calibrated, which the Sub-Committee do not consider to be practicable. Pure tin wire seems

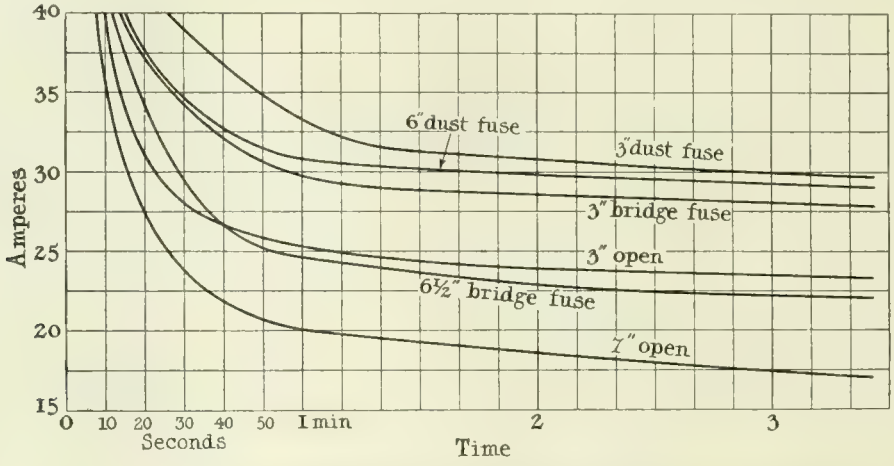


FIG. 3.—Fusing currents of a 0·064 in. pure tin wire up to 3 minutes.

It follows, therefore, that the use of a copper fuse involves the need for setting it to break the circuit at a higher value of the current it will permanently carry, and this no doubt accounts for the fact, pointed out by Mr Ram in the above letter, that it is common practice to use fuses set to open the circuit at 3 times the working load.

most nearly to meet our requirements: the melting point is low, the metal is strong and not too ductile, and it is practically free from deterioration at temperatures below the melting point.

In order to admit of the ready testing of a fuse, we consider it advisable to specify the current at which the fuse will melt in one minute from the application of

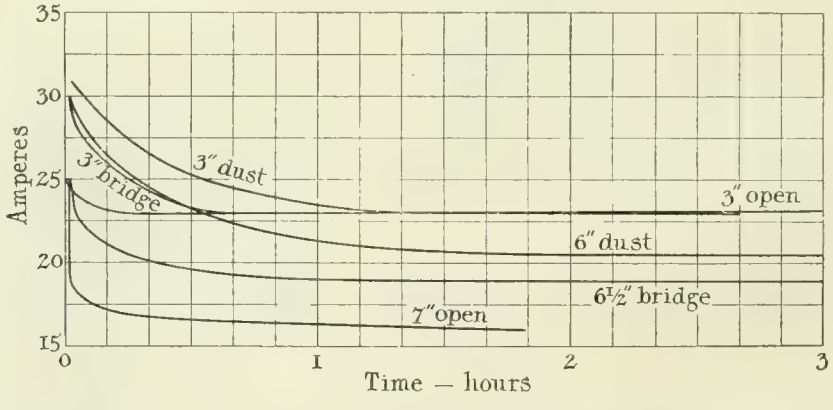


FIG. 4.—Fusing currents of a 0·064 in. pure tin wire up to 1 hour, and probable maximum carrying capacity.

For the type of fuse we have in mind, therefore, it seems evident that we must use a metal having a low melting point and one that is as nearly as possible non-oxidizable at any lower temperature than its melting point.

The choice appears to lie between lead, solder, and tin. Lead suffers from the disadvantage of being too soft for handling, and good connection not being obtainable when it is directly clamped under terminals, owing

the current, starting from cold, rather than the present practice of specifying the current at which it will eventually melt, as such a test carried out with reasonable accuracy would require hours for its completion.

Figs. 3 and 4 show some characteristic curves for tin fuse wire 0·064 inch diameter with different typical mountings.

Fig. 3 shows the fusing currents up to 3-minute intervals from the application of the current, and

TABLE 1.

SINGLE 0·064 INCH DIAMETER PURE TIN FUSE.

Type of Fuse	A Fusing Current (1 min.)	B Probable maximum carrying capacity	C Proposed working current 66·6 % of A	D Per cent overload allowed on Cable
	amp.	amp.	amp.	
6½ in. bridge	25	19	16·66	14·05
3 in. ,,	30	23	20·0	15·00
7 in. open	20	16	13·33	20·00
3 in. ,,	25	23	16·66	38·00
			50 per cent of A	
6 in. dust	31	20·5	15·5	32·25
3 in. ,,	34	23·0	17·0	35·25

TABLE 2.

TYPICAL SIZES OF SINGLE RUBBER-INSULATED LEAD-COVERED CABLES. (TABLE IVA. B.E.S.A. REPORT, NO. 7. REVISED MARCH 1910.)

Size of Conductor	Area of Conductor	Thickness of Lead	Diameter over Lead	Area of Lead Sheath		Resistance of Lead Sheath per 1,000 Yards	Current		Length of Cable to give Current I_1	
				Lead	Copper Equivalent *		Allowed by I.E.E. Rules = Working Current	Fault Current to blow fuses. I_1 = Working Current plus 50 per cent	With Voltage of 100	With Voltage of 200
S.W.G.	sq. in.	in.	in.	sq. in.	sq. in.	ohms	amp.	amp.	yd.	yd.
1/18	0·0018	0·031	0·196	0·0161	0·00129	18·6	7·2	10·8	500	1,000
1/17	0·0025	0·031	0·206	0·017	0·00136	17·7	9·8	14·7	385	770
3/20	0·003	0·033	0·236	0·021	0·00168	14·3	12·0	18·0	390	780
7/18	0·0125	0·037	0·330	0·034	0·00272	8·85	34·0	51·0	222	444
19/16	0·06	0·047	0·562	0·076	0·0061	3·94	83·0	124·5	204	408
19/13	0·125	0·056	0·748	0·122	0·00975	2·46	134·0	201·0	202	404
37/14	0·182	0·062	0·888	0·161	0·0129	1·86	172·0	258·0	208	416

* Conductivity of lead taken as 8 per cent that of copper.

TABLE 3.

TWIN RUBBER-INSULATED LEAD-COVERED CABLES FOR HOUSE WIRING. (TABLE IVA. B.E.S.A. REPORT.)

Size of Conductor	Area of Conductor	Thickness of Lead	Diameter over Lead	Area of Lead Sheath		Resistance of Lead Sheath per 1,000 Yards	Current		Length of Cable to give Current I_1	
				Lead	Copper Equivalent *		Allowed by I.E.E. Rules = Working Current	Fault Current to blow fuses. I_1 = Working Current plus 50 per cent	With Voltage of 100	With Voltage of 200
S.W.G.	sq. in.	in.	in.	sq. in.	sq. in.	ohms	amp.	amp.	yd.	yd.
1/18	0·0018	0·031	0·370	0·033	0·00264	9·10	7·2	10·8	1,020	2,040
1/17	0·0025	0·031	0·392	0·035	0·0028	8·60	9·8	14·7	790	1,580
3/20	0·003	0·033	0·448	0·043	0·00345	6·95	12·0	18·0	800	1,600
7/18	0·0125	0·037	0·638	0·070	0·0056	4·30	34·0	51·0	456	912
19/16	0·06	0·047	1·168	0·165	0·0132	1·82	83·0	124·5	442	884
19/13	0·125	0·056	1·544	0·260	0·0208	1·155	134·0	202·0	432	804
37/14	0·182	0·062	1·820	0·340	0·0272	0·885	172·0	258·0	438	876

* Conductivity of lead taken as 8 per cent that of copper.

TABLE 4.

SIMILAR DETAILS WORKED OUT FOR VULCANIZED INDIARUBBER BRAIDED CABLES IN STEEL CONDUIT.

Size of Conductor	Area of Conductor	Size of Conduit (Outside Diameter)	Area of Conduit	Copper Equivalent of Conduit †	Resistance of Conduit per 1,000 Yards	Current		Length of Conduit to give Current I_1	
						Allowed by I.E.E. Rules = Working Current	Fault Current to blow fuses. I_1 = Working Current plus 50 per cent	With 100 volts	With 200 volts
S.W.G.	sq. in.	in.	sq. in.		ohms	amp.	amp.	yd.	yd.
3/20	0·003	$\frac{5}{8}\times 0\cdot064$	0·112	0·014	1·72	12·0	18·0	3,240	6,480
7/18	0·0125	$\frac{7}{8}\times 0\cdot072$	0·181	0·0226	1·065	34·0	51·0	1,840	3,680
19/16	0·06	$1\frac{1}{2}\times 0\cdot08$	0·357	0·0445	0·540	83·0	124·5	1,490	2,980
19/13	0·125	$2\times 0\cdot092$	0·550	0·0685	0·350	134·0	201·0	1,420	2,840

† Steel taken as having $12\frac{1}{2}$ per cent conductivity of copper.

TABLE 5.

LOW-TENSION SINGLE PAPER-INSULATED AND LEAD-COVERED CABLES. (TABLE IIIA. B.E.S.A. REPORT.)

Size of Conductor	Area of Conductor	Thickness of Lead	Diameter over Lead	Area of Lead Sheath		Resistance of Lead Sheath per 1,000 Yards	Current		Length of Cable to give Current I_1	
				Lead	Copper Equivalent *		Allowed by I.E.E. Rules = Working Current	Fault Current to blow fuses. I_1 = Working Current plus 50 per cent	With Voltage of 100	With Voltage of 200
S.W.G.	sq. in.	in.	in.	sq. in.	sq. in.	ohms	amp.	amp.	yd.	yd.
1/18	0·0018	0·06	0·35	0·0545	0·00435	5·52	7·2	10·8	1,680	3,360
3/20	0·003	0·06	0·38	0·060	0·0048	5·00	12·0	18·0	1,110	2,220
7/18	0·0125	0·06	0·44	0·0715	0·0057	4·21	50·0	75·0	317	634
7/16	0·022	0·06	0·49	0·081	0·0065	3·70	75·0	112·5	240	480
sq fn.										
0·05	0·05	0·06	0·50	0·100	0·008	3·00	120·0	180·0	186	372
0·10	0·10	0·07	0·75	0·150	0·012	2·00	191·0	286·5	175	350
0·25	0·25	0·09	1·05	0·272	0·022	1·09	343·0	514·5	179	358
0·50	0·50	0·10	1·36	0·395	0·032	0·75	540·0	810·0	165	330
0·75	0·75	0·11	1·57	0·500	0·04	0·60	738·0	1,107·0	150	300
1·00	1·00	0·12	1·82	0·640	0·051	0·47	932·0	1,398·0	152	304

* Conductivity of lead taken as 8 per cent that of copper.

TABLE 6.

LOW-TENSION TWIN PAPER-INSULATED LEAD-COVERED CABLES. (TABLE IIIA. B.E.S.A. REPORT.)

Size of Conductor	Area of Conductor	Thickness of Lead	Diameter over Lead	Area of Lead Sheath		Resistance of Lead Sheath per 1,000 Yards	Current		Length of Cable to give Current I_1	
				Lead	Copper Equivalent *		Allowed by I.E.E. Rules = Working Current	Fault Current to blow fuses. I_1 = Working Current plus 50 per cent	With Voltage of 100	With Voltage of 200
S.W.G.	sq. in.	in.	in.	sq. in.	sq. in.	ohms	amp.	amp.	yd.	yd.
3/20	0·003	0·08	0·60	0·130	0·0104	2·30	12·0	18·0	2,420	4,840
7/18	0·0125	0·08	0·63	0·138	0·011	2·18	50·0	75·0	610	1,220
7/16	0·022	0·08	0·7	0·155	0·0124	1·94	75·0	112·5	460	920
sq. in.										
0·05	0·05	0·09	0·87	0·220	0·0176	1·37	120·0	180·0	405	810
0·10	0·10	0·10	1·08	0·308	0·0246	0·975	191·0	286·5	360	720
0·25	0·25	0·13	1·51	0·562	0·045	0·535	343·0	514·5	364	728
0·50	0·50	0·15	1·95	0·840	0·067	0·358	540·0	810·0	345	690

* Conductivity of lead taken as 8 per cent that of copper.

Fig. 4 the fusing currents up to 1 hour and the probable maximum carrying capacity.

The results are set out in Table 1, from which it can be seen that a sufficient allowance for determining the working current is to deduct 33⅓ per cent from the 1-minute fusing current, which will make the fusing current 50 per cent above the working current. This gives with a tin fuse wire a sufficient margin over the working current to allow for variables, such as size, etc., for all types except dust fuses. This type of fuse, not being generally used in connection with wiring a given size of wire cannot be stated unless both its environment and length are known.

The Sub-Committee therefore recommend that the Institution Rules should specify the use of pure tin fuse wires only, and that these should be so proportioned to their type of mounting, for all sizes of fuses, that they will interrupt the current in one minute from the first application of a current 50 per cent above the maximum working current allowable by the Rules to be carried by the smallest section of cable protected by the fuse.

TABLE 7.

PAPER-INSULATED CABLES.

Working Conductor				Bare Earth Wire				
Size of Conductor	Area of Conductor	I.E.E. Working Current for Paper insulated Cables	Fault Current—Working current plus 50 per cent	Theoretical Area to give 300 deg. F. rise in Temperature with 50 per cent above Working Current flowing continuously	Nearest Size of Conductor and Equivalent Area of the same		Total Area of Earth Wires in Column (e)	Relative Size of Earth Wire to Conductor
(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)
S.W.G.	sq. in.	amp.	amp.	sq. in.	No. and S.W.G.	sq. in.	sq. in.	per cent
1/18	0·0018	7·2	10·8	1 condr. 0·00104	1 × 1/14	1 × 0·005	0·00104	57·8
1/16	0·0032	12·0	19·35	0·002256	1 × 1/14	1 × 0·005	0·002256	70·5
7/22	0·0042	17·0	25·5	,, 0·003257	1 × 1/14	1 × 0·005	0·003257	77·5
7/20	0·007	28·0	42·0	,, 0·00632	1 × 7/20	1 × 0·007	0·00632	90·2
7/18	0·0125	50·0	75·0	,, 0·01379	1 × 7/17	1 × 0·017	0·01379	110·2
7/16	0·022	75·0	112·5	,, 0·0238	1 × 7/15	1 × 0·028	0·0238	108·1
7/14	0·035	97·0	145·5	0·03366	1 × 7/14	1 × 0·035	0·03366	96·2
7/0·097	0·05	120·0	180·0	,, 0·04449	1 × 19/17	1 × 0·046	0·04449	89·0
19/16	0·06	135·0	202·5	2 condr. 0·02061	2 × 7/16	2 × 0·022	0·04122	68·7
19/15	0·075	157·0	235·5	2 ,, 0·02531	2 × 7/15	2 × 0·028	0·05062	67·4
19/0·083	0·100	191·0	286·5	2 ,, 0·03285	2 × 7/14	2 × 0·035	0·0657	65·7
19/13	0·125	219·0	328·5	2 ,, 0·03941	2 × 19/17	2 × 0·046	0·07882	63·1
37/15	0·15	246·0	369·0	2 ,, 0·04581	2 × 19/17	2 × 0·046	0·09162	61·0
37/0·083	0·2	296·0	444·0	3 ,, 0·0343	3 × 7/14	3 × 0·035	0·1029	51·4
37/0·092	0·25	343·0	514·5	3 ,, 0·04173	3 × 19/17	3 × 0·046	0·12519	50·1
37/0·104	0·30	385·0	577·5	4 ,, 0·03317	4 × 7/14	4 × 0·035	0·13268	44·2
61/0·092	0·40	464·0	696·0	4 ,, 0·04246	4 × 19/17	4 × 0·046	0·16984	42·4
61/0·104	0·50	540·0	910·0	5 ,, 0·03871	5 × 19/17	5 × 0·046	0·19355	38·7
61/0·112	0·60	624·0	936·0	5 ,, 0·04676	5 × 19/17	5 × 0·046	0·2338	38·9
91/0·101	0·75	738·0	1,107·0	6 ,, 0·04581	6 × 19/17	6 × 0·046	0·27486	36·6
91/0·108	0·80	776·0	1,164·0	7 ,, 0·04012	7 × 19/17	7 × 0·046	0·28084	35·1
91/0·118	1·00	932·0	1,398·0	8 ,, 0·04264	8 × 19/17	8 × 0·046	0·34112	34·1

NOTE.—The areas of wires stated in column (*e*) are calculated upon the assumption that the numbers of separate conductors stated are used, and so spaced from each other as to have an inappreciable heating effect on each other.

Column (*f*).—If strip earthing conductors are used they should not be of less section than Column (*e*).

work, can either be ignored in the Institution Rules or, preferably, be provided for by making the working current 50 per cent of the 1-minute current for this type of fuse, which would then give a sufficient margin between the working current and the current at which the fuse would ultimately open the circuit with a prolonged load.

It will be seen from the curves in Figs. 3 and 4, that the environment of a fuse has a marked effect both on its ultimate carrying capacity and on the value of the current at which it will break circuit in a given time. It is therefore desirable that any new Rules should make it clear that a standard fusing current for

The Sub-Committee also recommend that where mechanical circuit breakers are used they shall be so designed that the conductors protected by them cannot exceed the limits of temperature allowable with wire fuses, that is to say, a circuit breaker can safely operate with an increasing overload the shorter its time element: in round figures 250 per cent if the circuit is to be opened in 10 seconds from the time of the overload and 400 per cent if in 5 seconds, but the Sub-Committee recommend that 400 per cent should be the extreme limit of overload however much less than 5 seconds the time element may be.

It will be seen on reference to Table 1 (Col. D) that

the worst case we have to meet is the type of fuse-mounting which allows of a prolonged overload of 38 per cent above the working current on the cables; and, following the formula already referred to in connection with calculations of temperature, we find that this will give us an increase of 36 degrees F. in the case of rubber cables and 95 degrees F. in the case of paper cables. Assuming the atmospheric temperature of 80° F. already referred to, we have a maximum temperature of 116° F. for rubber cables and 175° F. for paper cables, which compare with the maximum working temperatures laid down in Rule 44 of 130° F. and 176° F. respectively.

We have investigated the carrying capacities of conduits and the lead coverings of cables, and particulars are given in Tables 2, 3, 4, 5 and 6. From these it will be seen that, provided the path of a leakage current equal in volume to the main current does not exceed the lengths given in the last two columns, the current traversing the sheathing or conduit is bound to exceed the carrying capacity of the fuse, and the circuit will therefore be opened before any undue heating can take place.

Theoretically, for each size of cable sheathing or conduit a different length can safely be worked with one earth, but as the minimum length of 150 yards for any one size at the lower voltage is well within the limits of practical requirements in all but very exceptional cases, we suggest that it be adopted as the maximum length allowable.

As the wire armouring when used on rubber-covered cables has a carrying capacity in excess of that provided by lead covering if used, we suggest that the same rule should apply.

The Sub-Committee are of opinion that the Rules should clearly state that tape armouring must not be used for earthing purposes.

Tables 7 and 8 give particulars of the sizes of earth wires required for various sections of working conductors, paper and rubber insulated respectively. In the case of paper cables, owing to the larger working current allowed, the earth wires need to be larger than for rubber-insulated cables, and even larger than the working conductor itself in the smaller sizes. Earth wires for both types become progressively smaller relatively to the working conductor as the size of the latter increases. (It should be noted that the first 5 sizes are out of proportion owing to the carrying capacity having been worked out in the Wiring Rules Tables at 4,000 amperes per square inch instead of on

TABLE 8.

RUBBER-INSULATED CABLES.

Working Conductor				Bare Earth Wire				
Size of Conductor	Area of Conductor	I.E.E. Working Current for Rubber-insulated Cables	Fault Current = Working Current plus 50 per cent	Theoretical Area to give 300 deg. F. rise in Temperature with 50 per cent above Working Current flowing continuously	Nearest Size of Conductor and Equivalent Area of the same		Total Area of Earth Wires in Col. (*e*)	Relative Size of Earth Wire to Conductor
(*a*)	(*b*)	(*c*)	(*d*)	(*e*)	(*f*)	(*g*)	(*h*)	(*i*)
S.W.G.	sq. in.	amp.	amp.	sq. in.	No. and S.W.G.	sq. in.	sq. in.	per cent
1/18	0·0018	7·2	10·8	1 wire 0·00104	1 × 1/14	1 × 0·005	0·00104	57·8
1/16	0·0032	12·9	19·35	,, 0·002256	1 × 1/14	1 × 0·005	0·002256	70·5
7/22	0·0042	17·0	25·5	,, 0·003257	1 × 1/14	1 × 0·005	0·003257	77·5
7/20	0·007	24·0	36·0	,, 0·00515	1 × 3/18	1 × 0·0053	0·00515	73·5
7/18	0·0125	34·0	51·0	,, 0·00835	1 × 7/19	1 × 0·0086	0·00835	66·8
7/16	0·022	46·0	69·0	,, 0·01245	1 × 7/18	1 × 0·0125	0·01245	56·6
7/14	0·035	60·0	90·0	,, 0·01766	1 × 7/16	1 × 0·022	0·01766	50·5
7/0·097	0·05	74·0	110·0	,, 0·0232	1 × 7/0·068	1 × 0·025	0·0232	46·4
19/16	0·06	83·0	124·5	,, 0·0275	1 × 7/15	1 × 0·028	0·0275	45·8
19/15	0·075	97·0	145·5	,, 0·0336	1 × 7/14	1 × 0·035	0·0336	44·8
19/0·083	0·100	118·0	177·0	,, 0·0433	1 × 19/17	1 × 0·046	0·0433	43·3
19/13	0·125	134·0	201·0	2 wires 0·0204	2 × 7/16	2 × 0·022	0·0408	32·7
37/15	0·15	152·0	228·0	,, 0·0243	2 × 7/0·068	2 × 0·025	0·0486	32·4
37/0·083	0·2	184·0	276·0	,, 0·0314	2 × 7/14	2 × 0·035	0·0628	31·4
37/0·092	0·25	214·0	321·0	,, 0·0380	2 × 19/17	2 × 0·046	0·0760	30·4
37/0·104	0·30	240.0	360·0	,, 0·0445	2 × 19/17	2 × 0·046	0·0890	29·7
61/0·092	0·40	288·0	432·0	3 wires 0·033	3 × 7/14	3 × 0·035	0·0990	24·7
61/0·104	0·50	332·0	498·0	,, 0·040	3 × 19/17	3 × 0·046	0·120	24·0
61/0·112	0·60	384·0	576·0	4 wires 0·033	4 × 7/14	4 × 0·035	0·132	22·0
91/0·101	0·75	461·0	691·5	,, 0·0422	4 × 19/17	4 × 0·040	0·1688	22·5
91/0·108	0·80	488·0	732·0	,, 0·0452	4 × 19/17	4 × 0·046	0·1808	22·6
91/0·118	1·00	595·0	892·5	5 wires 0·044	5 × 19/17	5 × 0·046	0·220	22·0

NOTE.—The areas of wires stated in column (*e*) are calculated upon the assumption that the numbers of separate conductors stated are used, and so spaced from each other as to have an inappreciable heating effect on each other.

the formula—see Wiring Rule 43—whereas all the other and larger sizes are in our table worked out upon Melsom & Booth's formula both for main conductor and for earth wires.)

Two alternative rules can be formulated. One is a series of approximations such as :—

No earth wire shall be less than 1/14 S.W.G. Subject to this, earthing conductors for paper cables shall, for all sizes of working conductors up to and including 0·05 square inch, be equal in area to the working conductor.

For sizes from 0·05 up to and including 0·15 square inch, they shall be equal to 66 per cent, and, for sizes over 0·15 square inch, equal to 50 per cent.

Subject to the same limitation as to 1/14 S.W.G. being the minimum, earthing conductors for rubber-insulated cables shall, for 0·0125 and 0·022 square inch working conductors, be equal in area to 66 per cent of the main conductor.

For sizes 0·035 to 0·10 sq. in. inclusive ..	50%
For sizes 0·125 to 0·3 sq. in. inclusive ..	33%
Above 0·3 sq. in.	25%

The Sub-Committee, however, think that a specified size and number of earth wires should be named for each size of main conductor, and the particulars given in the form of a column to be added to the particulars of carrying capacity, etc., of conductors given in the Appendix to the I.E.E. Wiring Rules.

Upon the assumption that the foregoing suggestions are adopted, we recommend that :—

(1) Earthing conductors must be of the numbers and sizes set forth in the tables attached to the rules for each size of working conductor.

(2) That they should be of high conductivity copper, tinned or otherwise protected against corrosion, and protected against mechanical injury.

(3) That the smallest allowable size of earthing conductor should be 1/14 S.W.G., and the largest individual conductor should be 19/17 S.W.G., and that all conductors larger than 1/14 S.W.G. should be stranded.

(4) When a larger section of earthing conductor than 19/17 S.W.G. is necessary, separate conductors must be used, and if earth plates or cylinders are employed, separate ones for each conductor must also be used.

(5) Buried earth plates or cylinders must have an earth contact of not less than 4 square feet, and be surrounded on all sides by not less than 12 inches' depth of finely broken coke. They should preferably be of cast iron or other durable metal and the place selected for burying them must be permanently wet or, at least, damp.

[Note : We have deleted the requirement of the present rule to the effect that the coke used must be free from sulphur. The sulphur now contained in coke does not in practice exceed 2 per cent and it is not in such chemical form as to be readily converted into sulphuric acid.]

(6) Wherever an earth wire is connected to a pipe, or conduit, or cable sheath, or armouring, a substantially designed clip must be used. Sweating sockets also must be used at each end of the earth conductor for all sizes larger than 1/14 S.W.G. For armoured cables substantial clamps must be used, so designed as to grip firmly the whole of the wires of the armouring without damage to the insulation.

(7) Where special earth plates are not provided, extreme care must be taken to see that only such earths are used as are easily capable of carrying the maximum current which can be allowed to flow by the largest fuse used in the circuit in question. From this point of view water pipes directly in connection with the street water-mains make excellent earths. Steel frameworks of buildings must not be used as earths.

In conclusion the Sub-Committee strongly recommend that Rule 2 (*b*), providing for the need of earthing all metal other than the conductor on circuits where medium pressures are used, be extended to include low-pressure circuits also, and that it also be extended to prescribe the earthing of all metal liable to be electrically charged, such as constructional steel-work.

[The discussion on this Report will be found on page 476.]

Discussion on Mr. Milne's Paper and the Report on "Earthing," before The Institution, 25 March, 1920.

Mr. J. W. Beauchamp : The subject of Mr. Milne's paper is of extreme interest, and is one which will be of very real money value to the industry in the near future. The author has put forward some figures of great value with regard to the cost of wiring. In collecting figures I have found a very great diversity of opinion as to what is a reasonable price for wiring working-class houses. Some contractors quote prices, for what are generally known as the cheaper systems, greater than those one would expect to pay for tube systems. I think that is due to the fact that very little experience has been achieved in wiring large numbers of houses *en bloc*, and also to the disturbance produced by shortened hours and changes of wages. We really have to find out the price at which we can do this class of work. It appears obvious, however, that more and more of the money must be spent in the factory and less and less on the actual building site. That is the underlying meaning of all surface wiring systems : to devise cable and fittings that can be handed to the wiremen almost as a complete installation only needing to be fixed up. The figures the author has put before us amount in the highest case to about 3 per cent on a £700 house, and in the lowest case to about 1 per cent—an extremely small increase in the cost of the house. Those are the figures for wiring, but one really ought to talk of the difference between wiring and, say, piping for gas, inasmuch as if these houses do not have electricity they will almost certainly have gas ; so that we are only dealing with the difference, if any, a very small percentage on the total cost. I should like to emphasize in every possible way the urgency of getting electric light into these new working-class dwellings. Even if there is a difficulty—as there will be for some time—in getting electric heating and cooking apparatus installed in some of the colonies, we ought to make every endeavour and spend money, if necessary, to get electric light installed. If electricity is adopted for lighting, other uses will probably follow. Whereas, if we do not get the lighting, electrical apparatus may be kept out of these houses for 10 years. Some interesting figures appeared in the daily Press this morning with regard to the amount of business to be done in these working-class houses. We have been promised 100,000 this year, and altogether half a million are wanted. Assuming that only one quarter of a million are within the reach of electricity supply, there is something like $2\frac{1}{2}$ million pounds worth of electrical work waiting for the manufacturers and contractors and the workmen employed on the houses, and that for lighting only. Lamp renewals and energy must also represent very important business. Whether we get these working-class houses or not for electricity depends, I think, not on the excellence of electric light—most people are convinced on that score—but on those who have the giving out of the work—local representatives, members of Councils, labour people, and others interested in the erection of houses. Those people, with their architects and surveyors, have got to be shown that the use of electric light in these houses will be for the benefit of the people's health, will mean that, if necessary, lower ceilings can be used, and will save money in upkeep and decoration. Presumably the maintenance of these houses will be undertaken by the local authorities, and they will probably get a higher rent than they at present expect, if the houses are really well designed and fitted with labour-saving equipment. It is possible that these houses may not be immediately remunerative to the supply undertakings, but it would be well worth while for them to secure the business and to persuade the local authorities and other bodies interested to allow as much money as possible for installations, and to see that a proper supply is given. As the years go by we shall get better and cheaper electric cooking apparatus, and we may find the hot-water problem partly solved by the use of waste heat from the generating stations or by storage systems and 24-hour supply methods.

Mr. G. S. Ram : I should like to explain how the question of earthing came to be taken up by the Institution. In inspecting electrical installations I have often noticed that the size of the earth wires appeared to be too small. I have in some cases found earth wires which have been fused. I know of at least two fatal accidents from shock where the earth wires connected to the apparatus concerned were fused, and consequently failed to prevent the accidents. When considering what sizes of wires should be used as conductors for the circuits, contractors look to the table in the Institution Wiring Rules, and it is only natural that they should do the same with regard to the sizes of earth wires that ought to be installed. It is well known that the table giving sizes of conductors was worked out on a scientific basis from experiments carried out at the National Physical Laboratory, and those sizes are generally accepted ; but the sizes for earth wires do not appear to have been worked out on any such basis. The sizes for earth wires in Rule 34 seemed to me to be altogether too small, and, as far as I could see, they were so small that the wires might even fuse. I therefore wrote to the Institution suggesting that the matter should be considered by the Wiring Rules Committee, with the result that a small Sub-Committee was formed to go into the matter, and the Report now under discussion is the report of that Sub-Committee. The first thing the Sub-Committee did was to make experiments on earth wires on the basis of the existing Rule. It was proved first of all that my surmise was correct ; that the earth wires would get very much too hot. The temperature which a conductor or earth wire will reach is dependent on the maximum current it is allowed to carry and the time during which that current flows, and these limitations depend upon the latitude allowed by the existing regulation as regards fuses. Rule 98(*b*) permits double the working current, or more precisely anything just under double the working current

to flow for an unlimited time. It was then worked out and found that under these conditions the circuit conductors would get too hot—that is to say, they would get hotter than the limit prescribed in Rule 44. In order to get over that difficulty, three suggestions are made in the Report, the third being the one that is recommended, namely, that the margin for fuses should be reduced. If that is done, the existing sizes for the circuit conductors can remain. The Report is based on the assumption that this proposal will be adopted, and the corresponding sizes for earth wires are worked out accordingly. The limit of temperature proposed for earth wires is that of the melting point of solder. The diagram (Fig. A) gives an idea of the relative sizes of the conductor and earth wires. Curve No. 1 is based on the existing rule for the size of rubber-covered conductors; No. 2 is for paper-insulated conductors; No. 3 shows the proposed corresponding size for earth wires;

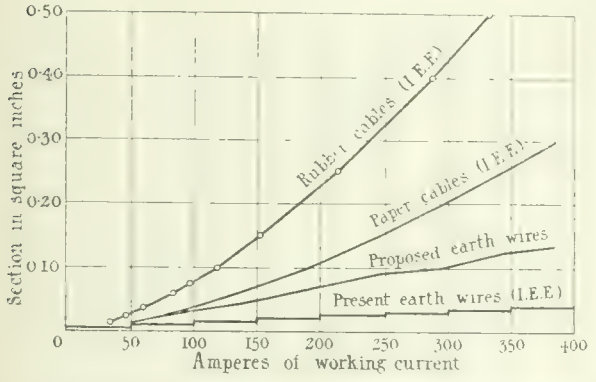


FIG. A.—Diagram showing I.E.E. sizes of conductors and earth wires, and the Sub-Committee's proposed sizes of earth wires.

and No. 4 shows the existing rule for earth wires, rising by steps. In conclusion, I would say that a great deal of trouble was taken over the matter, and a large number of experiments were carried out by Mr. Nisbett, many more than are indicated in the Report.

Mr. H. H. Berry: In the first place I should like to refer to Mr. Milne's suggestion in connection with encased cleat wires for ordinary dwellings. Personally, I think it is excellent. My chief desire in speaking on that point is to invite comments for consideration by the Wiring Rules Committee, as I am sure that the Committee would be only too glad to receive any helpful suggestions on this particular point. The correspondence which is now being considered by the Sub-Committees appointed in connection with the revision of the Wiring Rules, shows a considerable expression of opinion in regard to the necessity of providing adequate double-pole switches on the heating circuits in the ordinary house. We are informed in this correspondence that the Institution Rule is practically never observed. The reason why it has not been practicable up to the present to install a double-pole switch having a greater carrying capacity than, say, 2 kw. on each heater in a room, is that there is no such switch on the market. Consequently the Rule has been ignored, and naturally the members of the Committee desire to have all the assistance they can in rectifying little anomalies like that. Mr. Milne says in his paper: "A meter for each separate consumer is a heavy charge for the anticipated revenue, and where lighting only is installed consumers might be charged a fixed annual rate and a meter eliminated." He points out that in certain cases this has led to extravagant consumption and to the dishonest use of lighting points for electric kettles and so forth. I quite see his point in that respect, and it is a very useful one; but I desire to make a suggestion for his consideration. I suggest the use of a special adapter on the principle of the "fixed price" lampholder, which allows only a certain utensil of a given carrying capacity to be applied to that particular lampholder. It seems to me that an adapter might be made so that it would be possible to have, as it were, a fixed-price piece of apparatus that is non-interchangeable. With regard to Mr. Milne's suggestion that it is desirable, where possible, to avoid installing two meters, one for lighting and one for power, I think everything that can be done to further that end should receive our united support. There is no doubt that at present progress is retarded by the fact that in small houses there has to be practically a double installation, with the result that the average price is increased by from 100 to 150 per cent. Unless that difficulty is met, electricity in the home must receive a very serious set-back. Mr. Milne suggests the abolition of flues and chimneys, and mentions that perhaps the matter has not been receiving the consideration it deserves. There are many of us who have been devoting a great deal of thought to that particular subject. Personally it has been a matter of intense regard to me for the last year or two, and I have come to the conclusion that electricity in artisan dwellings is absolutely within our reach on an economical basis. There are one or two matters I should like to suggest which I do not think have been referred to in the paper. One is a system by which electricity can be used, as Mr. Milne has suggested, for the purpose of "topping up." I do not think he has referred, in connection with communal dwellings, to a suggestion that the primary heat for hot water should be supplied from some communal source. There are difficulties that will occur to all of us at once with regard to obtaining hot water which can be used for domestic purposes and also for raising the temperature of the house to about 55° F. Obviously, if a man has a free supply of hot water from a communal source, he may be extravagant and allow the water to be used unnecessarily. Devices have, however, already been introduced to deal with that problem; so that even the heat taken from a convector, which is often wrongly alluded to as a radiator, can be correctly metered and a charge made for the number of degrees F. of the room. The other point to which I wish to refer is communal supply. I have been devoting a great deal of attention to the application of that or similar supplies obtained from some such independent source as is suggested by the author, using the hot water received from that source to keep the electric cooker always hot, so that it is in reality a hot cupboard at all times, to which it is only necessary to apply electricity for

topping up. That reduces the current to a very considerable extent and also the time taken to cook. I apply the same method of heating to rooms, raising the temperature to 55° F., and replacing the appearance of a coal fire by something which has its practical equivalent in effect; so that we have radiant heat with which we can quickly raise the temperature up to the normal, which in this country is about 62° F. for a man of ordinary vitality.

Mr. J. Frith: I think the metering question in artisan dwellings could be very well solved by a maximum demand meter, a very much cheaper apparatus. It would be quite a good plan to charge merely on the maximum demand. With regard to the Report on "Earthing," the main thing on which the Report either stands or falls is the statement that the earth wire is provided primarily to open the circuit in the case of a fault. It has got to carry the current which blows the fuse or opens the circuit breaker, and that makes it essential to consider the question of earth wires along with the question of fuses. Mr. Ram has shown that the Institution Rules for the carrying capacity of cables and the carrying capacity of fuses are incompatible; one or other will have to be altered. We suggest in the Report that tin fuses should be used, which will open on a smaller overload. Copper, which is now in ordinary use, is not satisfactory when one is running a cable very near the dangerous load, as the Institution Rules quite rightly allow; we must have a fuse which will open nearer to its normal carrying capacity. The corollary of this is that the earth wire must safely carry the current which will open the fuse, and that does not seem to have impressed itself sufficiently on people's minds. It leads in some cases to a large earth wire, but that is much better than a fused earth wire and relying on protection which no longer exists. There is a small note at the end of the Report which I will emphasize, because it may escape notice, namely, that the rules for the provision of earth wires and the effective earthing of motor carcases, tubing for wiring and switchgear, should apply to all electrical apparatus and not only to those at medium voltage.

Mr. W. R. Rawlings: I do not approve of the system which the author advocates, namely, the open wire system or the cleat system, whichever he likes to call it. I suggest that any such wiring in artisan dwellings is likely to cause trouble. When run in a horizontal position, it would be convenient for hanging pictures. It would also form a splendid grip for a swing or a clothes' line. Any system which leaves a space between the wire and the wall is open to objection in artisan dwellings. I know it was used in the War Office, but only as a temporary measure. I am surprised the author has not referred to some of the well-known systems of a solid character and low in price, namely, Henley's, Callender's, and the Stannos systems. He might have referred to the fixed-price light system, which I suggest is one that will overcome many of the difficulties referred to in the paper. This system eliminates all main switches, meters, and meter readers, and there is only one service for each block of houses. A single Stannos wire is run along the face or the rear of the buildings, a tee joint is made for each house, and a single Stannos wire (the outer being used as the return conductor) is taken inside the building, a single-pole fuse being attached from which the wiring for the usual four or six lamps is run. I am well aware that a one-wire system could only be adopted with alternating current. This system is, in my opinion, the only one which deals with the problem of supplying electricity to artisan dwellings, as the cost of meters, main switches, and a separate service to each house is really prohibitive. I will now proceed to the Report on "Earthing." The information contained in the Report cannot be found in any textbook, namely, the conductivity of the lead sheathing and conduits. The Sub-Committee have also shown that the present Wiring Rules as to earthing should be altered, having regard to the overload allowed on fuses in conjunction with the sizes of earth wires. I, for one, am convinced that the facts and arguments set forth, backed up as they have been with a great amount of research, will be accepted by the Wiring Rules Committee. Among other things which must be seriously considered is the recommendation of the Sub-Committee that the fuse wire should be reduced to a 50 per cent overload. I am not sure that that is a sufficient margin to allow for oxidation and damage in connecting up. As Mr. Frith and Mr. Ram have rightly pointed out, the fuse and the earth wire must be jointly considered.

Mr. H. J. Cash: One part of Mr. Milne's paper in particular is of great interest to me. I believe the author is right in suggesting that on the neutral side of systems there is an enormous number of faults which we know nothing about and which are never repaired, for the simple reason that they do not declare themselves. In the case of the very small percentage of installations that are regularly tested, they are of course discovered. The author states that he "cannot find any case in which it has been observed that the occurrence of a fire was coincident with the development of a fault between the outer and neutral on the system." I think that point is of extreme interest, and I hope some of the Fire Office authorities will give us their views on it; because it appears that if there was no fault between the outer and neutral of the supply authority's system immediately prior to the fire, such fire could not have been caused by the altered potential of the neutral side of the house wiring, and the insulation of such neutral side becomes materially less important than some of us have thought in the past. Mr. Beauchamp has said that at all costs electricity must be got into artisan dwellings. I submit that if we are going to do it at all costs, the cutting down of the cost of the installation is a far better and more comprehensive measure to adopt than the spending of a large amount of money in propaganda. If we adopt propaganda, we shall persuade a certain percentage of the people who control these artisan dwellings to put in electricity; but we shall get a far larger percentage if we keep the cost of the electrical installation below that of gas, and that is what the author is driving at. With all respect to Mr. Rawlings, I doubt very much whether any of the existing systems can keep the cost down to the figure indicated by Mr. Milne's suggestion as regards the new form of wiring. Mr. Rawlings has

raised objections to open wiring. I quite agree, and I think that in all artisan dwellings open wiring should be avoided if possible. The author, however, has not committed himself to open wiring, and it appears to me he contemplates that the horizontal runs should be under the floors, the cleats being fixed half way down the joists, so that they are out of the way of the floor nails. Presumably the wire would go straight through the centre of the joists, still maintaining the insulation on a porcelain insulator. If his suggestion is adopted of a switch ceiling-rose, coupled with the horizontal running of cables under the floor, there would be practically no open wiring at all. The vertical runs disappear except when they come up from floor to floor in the insulated tubing. The switch ceiling-rose should be rapidly developed. I entirely agree with Mr. Milne that half the cost of the wiring installation, if not more, lies in the switch drop. A switch ceiling-rose has been put on the market, and in my opinion it should reduce the cost enormously. It may not have the same life as the ordinary tumbler switch which has been in use for 30 or 40 years and is now reaching perfection, but as soon as consulting engineers specify switch ceiling-roses I am confident that an equally good working article can be obtained. I do not altogether agree with Mr. Milne's suggestion that the switch ceiling-rose should be placed near to the door. I think the length of flexible cord along the ceiling should be reduced, and that it should be as near the point of light as possible. Its operation can be facilitated by simply extending the pull chain, if that is necessary. I very much doubt whether in the small rooms of artisan dwellings it is necessary to give operation at the door. Operation in the middle of one of the walls of the room is generally within 6 feet of the door. Another point is that Mr. Milne, by putting his switch ceiling-rose at the door, contemplates running a flexible cord across the ceiling obliquely. I suggest that such cords are too long and that they would also be unsightly. In discussing the question of two meters, one for lighting and one for power, Mr. Milne admits that the ideal system has still to be found. One of the serious difficulties is in connection with the size of the wire. If we are wiring a house cheaply for lighting we are up against a very considerable difficulty if we have to provide for heating services on the same wire, as we must if we are not to go in for expensive double wiring. I also entirely agree with Mr. Milne in the statement that "the stumbling-block to electrical cooking is the question of domestic hot-water supply." The principal difficulty there, I believe, could be solved. Electrical water heating in quantity is at the present moment in an experimental stage. Unfortunately, one cannot experiment on a really large scale; and only on a large scale can economy be obtained. The author's suggestion of an electrically-heated airing cupboard is also a subject which electrical engineers generally have overlooked. I believe an electrically-heated airing cupboard is the most economical form of heating that can be found, and yet the use of such articles is exceedingly small. In conclusion, the artisan is quite clever enough to remove a fixed-price lampholder and put in one of his own.

Mr. W. Cross (*partly communicated*): Mr. Milne suggests using a twin cable with one uninsulated conductor connected to the neutral side of the system, and that this neutral joint is always at earth potential. This is not the case in practice, as earthing is only permitted at the supply station or substation. In one instance it was found that without a fault on the system the neutral was 50 volts above earth due to unbalanced load on the mains. I therefore do not think it would be safe to connect an uninsulated conductor to the supply mains. The omission of the switch run down the wall will certainly appreciably reduce the cost of an installation, and I think that pull switches should be quite satisfactory in artisan dwellings. I do not like the idea of running flexible cable on insulated hooks, as it will almost certainly be damaged by the tenants. The costs given on page 464 are not excessive; and the one mentioned on page 465 seems to me to be optimistically low. I estimate that the cost of main and branch switches and fuses will be at least £4; if we omit the main switch and reduce this to £3 10s., the cost of cables, protection, sundries, and all labour will be only £3 10s. or 7s. 4d. per light, which is to-day little enough for labour only. I suggest that a system using metal-covered twin cable with the covering efficiently bonded and earthed is worth consideration. If an independent supply is given through a small transformer with one wire earthed, a metal-covered concentric system could be used, further reducing the cost. The cost of service cables is most important, and, in the figures given by the author, exceeds the cost of the installation. I think that in buildings such as we are considering, mains could be run through the false roof of a row of houses. I favour the use of a separate meter (which not need cost more than 45s.) for each consumer, unless the generating costs are very low indeed; and I am afraid trouble would result if a check meter were used for a section of tenants, each of whom would be interested in obtaining a rebate, and would think his neighbours used too much current. I believe that there would be little difficulty in making a fixed charge plus a small sum per unit, as all houses would be of similar type and rateable value; and this is certainly fairest to both the supply authority and the consumer. Electric cooking is very economical, clean, and saves labour; the consumption of current mentioned is high, the figure in practice being about 30 units per week for a family of 5 or 6 persons. I believe that owing to the more efficient generation of electricity and the utilization of waste heat for that purpose, the use of electricity in artisan dwellings will rapidly extend because it will be the cheapest and most efficient for illumination, cooking, and heating. To do this, the co-operation of architects, builders, supply authorities, and contractors is essential, so that the design of the house may be modified and the cost of service and installation reduced to as low a figure as possible with safe and good work.

The Report of the Earthing Sub-Committee is a valuable contribution to a subject that has received little attention, and appears to show that our existing Rules are unsatisfactory, as the temperature of earth wires may exceed the melting point of solder (about

392° F.). In practice, however, very few accidents occur through the small size of earth wires (most faults occur at joints or connections to apparatus, often badly carried out), but if the fuse be designed to blow at double the working current (three times in smaller sizes) in accordance with the present Rules, certain figures in the tables will be altered and the size of earth wire should be larger than that shown. It is assumed that fuses are used of a size which will not melt with the maximum current that the cable will carry. This is usually incorrect with the smaller cables, which are seldom fully loaded, the size of fuse being based upon the current taken by the apparatus protected by the fuse. I consider it to be most undesirable that a fuse should blow at 50 per cent above the working current; in many cases, especially on motor loads, the current at switching on is considerably greater than normal, and a margin must also be allowed for the deterioration of the fuse's carrying capacity during use. The Coal Mines Regulations call for an earthing conductor (separate cable or metal covering) having an area not less than half of one of the current-carrying conductors, with a minimum size of 0·022 square inch. I suggest that this rule could be adopted with the following modifications:—That up to 0·022 square inch inclusive, the earth conductor shall have the same conductivity as one of the current-carrying conductors, the smallest earth wire being 0·005 square inch for mechanical strength. The extra cost of this alteration to the old rule will not be great if expressed as a percentage of the cost of the job, and will certainly decrease the chance of accidents, especially if the conductivity of the earthing connections to the apparatus be improved. I do not think it is desirable to call for two earth wires when the area exceeds 0·046 square inch, as such a rule would not be observed, and there does not appear to be a good reason for it. It is often very difficult to find a good position for an earth plate, and I certainly do not think it necessary to fix as many as is suggested in the Report. Copper may theoretically be unsuitable for fuses, but in practice it is better than tin. Fig. 2 shows the behaviour of a copper fuse-wire melting at 36 amperes, the maximum working current being 18 amperes and the average current being probably less, and at this point the temperature of the wire is not excessive. It is an advantage for the fuse to oxidize and eventually melt at less than the initial melting point, as a continuous slight fault will then cause the fuse to blow. The hot metal is quite safe in the present patterns of fuse enclosure, and the damage done by a copper fuse when blowing is less than that done by a tin fuse owing to the smaller amount of metal set free. I agree with the statement in the last paragraph of the Report, that low-pressure circuits should be earthed, as the risk of accident is almost as great, and I believe that all metal enclosing electrical apparatus should be earthed, including the cases of meters and service fuses. I do not think it is possible, however, to enforce any rule for earthing constructional steelwork, as this is not erected by electrical firms.

Mr. F. Pooley: Cheap wiring has undoubtedly got to come, and very soon too. I have always been favourably disposed towards the cleat system of wiring, for many reasons. One is that there has been a lot of cheap wire on the market, and the more we have that in front of our eyes the better chance we have of looking after the troubles it causes. With regard to comparative costs, I should imagine that the figures given by Mr. Milne are fairly correct. I do not altogether like the idea of semi-insulation. Apart from the fact that the wire itself is very unsightly, I do not think we can depend on always getting the uninsulated wire on the neutral side of the system, assuming that there is a neutral side. Although, perhaps, in artisan dwellings appearance is not of quite so much importance as utility, it is not very difficult to anticipate damage being done to the visible wiring, but the artisan wants light, and if he hangs his clothes on the wire or swings things from it he will be without light for a time, so that I do not suppose he will do those things a second time. With regard to the question of ceiling-rose switches, a rotary switch operated by pulling a cord always in the same direction, such as was invented by Mr. Browett over 20 years ago, would do what Mr. Milne suggests. Co-operation between architects and wiring contractors would get over many of the difficulties in the way of using the cleat system, because if a main duct were provided in one position in a building from which the branch circuits could be taken it would be possible to use a high-class well-insulated rubber cable for the main leads in the duct, and a cheaper wire for distribution to the various points. I like the idea of grouping the houses and allowing a certain amount of electricity to be used on condition that if less were used a certain amount of money would be returned at the end of the quarter. The idea of making every neighbour a sort of detective is an excellent way of preventing the waste of current. With regard to the actual supply to these groups of houses, instead of running the wires along the chimneys I suggest that a better position is under the eaves, for two or three reasons. One is that no damage would be done to the roof, which is always a difficult question in connection with the repairs of houses. These wires running along under the eaves would be very much more accessible and could be reached by a ladder from the street. I do not know that the woman of the house would altogether like the idea of having the supply company's apparatus upstairs. I think the question of hot-water supply can be left to the hot-water engineers to deal with. They have already made considerable progress, and by the time we get the artisan dwellings I think we shall find the hot water is already there.

Mr. P. Rosling: I agree with what Mr. Milne says on the necessity of reduction in the cost of wiring, but I think it is necessary to consider the cost of maintenance as well as the first cost. I do not think we shall get architects and others concerned in the erection of these artisan dwellings to regard the open cleat system as being likely to be low in maintenance costs in an artisan dwelling. Mr. Milne has given some figures for different types of wiring, but he has not alluded to a class of wiring which has been on the market for 10 years and which has had a great deal of thought bestowed upon it, namely, the metal-covered twin wiring system. That system carries out to a certain extent

one of the requirements which has been suggested by a previous speaker, namely, that the equipment should be worked out in the factory so that it could be put up very quickly in the dwellings. Some costs that I have for one of the types of twin lead-covered cable came to just a little over those given for the open cleat system, which, I take it, allows for bringing the wire down to the switches. The single-wire concentric metal-covered system, which would compare with Mr. Milne's suggestion of twisting a 20-gauge wire round an insulated conductor and braiding it, brings the price down still lower, but it is only used at present in private installations off self-contained plants, or off a double-wound transformer. The cost of the twin-wire metal-covered system before the war was between 7s. 6d. and 15s. a point. That has risen now to something like 25s or 26s. a point, which does not come much over the author's figure for open cleat wiring. From statistics which I have before me there must be tens of thousands of artisan dwellings now wired with this metal-covered system, so that it is not new; it has been well tried; and the cost of upkeep and maintenance is practically nil.

With regard to the Report on "Earthing," I should like to raise a protest against insisting on the discontinuance of tinned copper wire for fuses. This has served the purpose very well, anyway in the smaller sizes up to now; there must be millions of copper-wire fuses in use, and I have not heard of many accidents occurring with them. It seems to me that sufficient allowance has not been made for the time element in the tables. We have made a test in a 10-ampere fuse box with a tinned copper fuse wire which will carry 10 amperes continuously; and with a current of 15 amperes we find the fuse blows in 2 minutes, while with 25 amperes it blows in 5 seconds, so that within the fusing time the cable or wire protected would not rise to a dangerous temperature.

Mr. G. H. Elliott: I agree with what has been said as to the desirability of doing away with the switches at hand height in the class of houses under discussion. This is really the only sort of thing we can do in artisan dwellings where there may be a number of mischievous children. By substituting a cord or rod we save all the troubles that they may cause. I would also suggest that the ceiling rose be eliminated as well. There is no necessity to use an expensive flexible cord; we could use the same twin wire up to the lampholder, simply looping it into the switch near the ceiling. We must remember that we have to provide something that will compare in cost, in appearance, and in durability with a $\frac{3}{8}$ in. gas tube. For the better-class houses there is another way of reducing costs. Up to the present, all switches and ceiling roses, etc., have been designed by people whose interest has finished when they have provided a terminal for the wire. No effort has been made to correlate the fitting with the protection for the wires. It has been necessary for the wireman to adapt and fit wood blocks, and spend a lot of time on work which can be much better done in the factory. Switches and similar fittings which are definitely designed with bases for direct entry of conduits, lead-covered wire, or any other approved protection for the wiring, would be of value in reducing costs and ensuring better work. With regard to the electric water-heating problem, we have to provide about $4\frac{1}{2}$ kw. for the oven, and have to supply hot water at times in good quantities for washing-up, spring-cleaning, etc. The ordinary 24-hour load water-heater is generally useless in case of heavy demand or emergency. Could we not use the $4\frac{1}{2}$ kw. for boosting up the hot water supply; it could be arranged with a throw-over switch in connection with the oven, so that it could not be kept on all the time, or a 9 kw. demand made on the mains.

Mr. G. C. Burnand: I absolutely agree with what Mr. Rawlings and Mr. Rosling have said in regard to cleat wiring. I do not think that cleat wiring in the ordinary working-class cottage would be a great success. I have had considerable experience in connection with the wiring of working-class dwellings, and I find that we are dealing there with quite a different class of person, who does not realize that the current is flowing in the wire at all. Mr. Rawlings mentioned the fixed-price light system, and there are one or two additional facts with regard to it which I should like to mention because I think they may be of interest to the members. I have had numbers of inquiries from engineers all over England in connection with the fixed-price light system, mainly for the purpose of working-class dwellings under the Government Housing Scheme. It may interest members to know that this system is in operation at Sevenoaks, Egham and Staines, Hindhead, and Leatherhead, and the Beckenham Urban District Council have, I believe, just been granted a loan from the Government to enable the Council to adopt the system in connection with their housing scheme. In the case of some of the towns mentioned there is a three-phase four-wire distribution, and where this is the case the Board of Trade have granted permission for them to work with a continuously earthed neutral. In such cases the whole of the wiring and distribution is carried out by a wire with metal sheath used concentrically without any transformers between the company's mains and the wiring, and there are of course no meters. As the author states, the objection to the fixed-price light system is that it might lead to extravagant consumption of current. In the cases I have in mind this objection has been partly overcome by the use of the specially designed lampholder mentioned by Mr. Berry, and it is found that there is no tendency for consumers to disconnect this lampholder and put in one of their own. I may say that I have never known this to happen, although there are some 4,000 or 5,000 consumers. At the same time a special lampholder makes it certain that the consumers cannot put a 50-watt lamp into a 30-watt socket, and as they have to buy all their lamps through the company a record is kept of the number of lamps that go out and of their life. I have found in practice that the tendency to leave lamps burning all night or for exceptionally long periods has been greatly exaggerated, and that the actual annual consumption of current per lamp is far less than one would anticipate. On the Wimbledon and Waterloo systems of the Fixed Price Light Company the average annual consumption of current works out at a little under 28 units per 30-watt lamp installed.

The figures obtained from the Waterloo and Rotherhithe districts, which are both decidedly working-class neighbourhoods, compare favourably with the figures obtained from the Wimbledon district, which is a better-class residential neighbourhood. The charges at Wimbledon average 4d. per 30-watt lamp and 5d. per 50-watt lamp per week, and I should be pleased to explain at any time the method employed in arriving at these figures, which I may say show a fair profit to the company. With regard to heating and cooking, the anticipated revenue would, as the author states, doubtless be sufficient to justify the cost of a meter, but at the same time I feel that with sufficient reliable data one could possibly evolve a scheme for charging on the fixed-price basis.

Mr. S. W. Melsom : The Sub-Committee on Earthing have produced a Report which is distinctly courageous if somewhat provocative of criticism, and they have probably done wisely in bringing earthing and fusing together. One really fundamental question is the definition of the function of an earth wire given on page 464 as follows : " The whole object of an earth wire is to enable a fuse to open the circuit." The present Wiring Rules obviously do not provide for this, and it is certain that any such definition will have to be carefully considered by the Wiring Rules Committee before it could be adopted. If, however, the definition is accepted, the work of drafting the clauses relating to earthing will be very much simplified, although the cost of an installation will probably be increased. The question is, however, not wholly one of the size of earth wires ; consideration must also be given to the resistance of the other portion of the circuit through which the current must flow. The Report is, in this respect, not altogether consistent, since the Sub-Committee provide only for a large-section conductor down to an earth plate (page 471), and appear to regard the remainder of the circuit as having no resistance. I felt rather dubious about the resistance of the earth when contact is made by means of an earth plate, and had two plates buried under the conditions suggested in the Report. The holes were cut right down on to the Thames ballast, with a protecting layer of clay above it, the soil being very wet. The plates were buried in coke, and were 15 feet apart. The resistance between plate and the coke was practically zero ; and between plate and plate it was 60 to 70 ohms. Obviously this resistance is far too high to allow of sufficient current to heat up a cable, and if earth plates are to be allowed it is clear that the size of earth wire permitted by the present Wiring Rules is more then sufficient. I have no definite figures for water pipes—these are no doubt of much lower resistance—but I doubt whether their resistance is sufficiently low ; and in the event of the Wiring Rules Committee adopting the proposal of the Sub-Committee and regarding the earth wire as a protector of the cable, it seems probable that some system of continuous conductor protector will be required if currents of the magnitude suggested in the Report are to be dealt with. Before going on to the question of fuses, I should like to say that I cannot agree with Mr. Frith's remarks that the present Wiring Rules allow of a current density which approaches the danger point for cables. Actually the temperature-rise with the currents allowed will be only 20 degrees F. for rubber-covered cables and 50 degrees F. for paper-insulated cables. The air temperature is taken to be 80° F., a figure which is higher than the normal air temperature in this country ; but even under these conditions the final temperature would be 100° F. for rubber cables and 130° F. for paper cables. The figures for safe temperature for the different types of cables are 130° F. and 180° F., so that there is a margin of 30 degrees F. for rubber cables and 50 degrees F. for paper cables. Not only have we a wide margin as regards heating, but it must be borne in mind—and this is a point which needs emphasis—that even if a particular wire attains for a short period the maximum temperature allowed by the Wiring Rules it is not necessarily ruined. The process of deterioration of a dielectric by a high temperature is very slow, and the cable would probably withstand, for a short time, without any appreciable change a higher temperature than the outside limits above mentioned. With regard to fuses, the Report suggests that tin fuse wire only should be allowed, a recommendation which is in

TABLE A.

Fusing and Safe Running Current for Fuses carried in Vitrified Earthenware Holders.

The fusing current was determined for various sizes of bare copper wire over a range of from 10 to 150 amperes. In these tests the fusing current was taken to be that which would melt a given size of wire in a period of approximately one minute.

Size of Wire	Fusing Current	Preece's Values from "Munro and Jamieson"
S.W.G.	Amps.	Amps.
32	10·8	11·5
30	13·2	14
28	17·0	18
26	23·7	24·7
24	31·2	33
23	35·5	—
22	44	48
21	52	—
20	65	70
19	78	—
18	103	107
17	129	—
16	161	166

The safe running current for the various sizes of wire may be taken as being from 55 to 60 per cent of the fusing current. The safe running current is that at which there is little or no oxidation of the fuse wire. With currents appreciably higher than from 55 to 60 per cent of the fusing current the decrease in section of the wire due to slow oxidation will result in the wire fusing at a lower current than that given above.

my opinion open to serious objection, since it will tend to prevent a better material being introduced. It is much better to specify the requirements for fuse metals and leave the manufacturers free to use any material that will comply with such requirements. The use of copper is almost universal, and there is little doubt that with properly designed fuse-holders and

TABLE B.

Energy Losses with Fuses of Various Lengths.

The loss is given for some of the larger sizes of fuses when running continuously at 60 per cent of their normal fusing current. The losses given for the fuse-wire lengths of $3\frac{1}{2}$ inches and 6 inches are calculated from the values obtained with the actual length of $4\frac{1}{2}$ inches, assuming for the purpose of calculation that the resistance of the fuse with the current flowing is in proportion to its length.

Watts lost in 12 Fuses at Normal Running Current, i.e. 60 per cent of Fusing Current

Size of Wire	Current	Length of Fuse between Terminals		
		$3\frac{1}{2}$ in.	Normal, $4\frac{1}{2}$ in.	6 in.
S.W.G.	Amps.			
16	96·5	148	190	253
18	62·3	107	138	184
19	47	83	107	142
20	39	72	92	123

TABLE C.

Temperature Rise in a Fuse Box.

The rise of temperature above that of the surrounding air was taken after eight fuses had been running continuously until the temperature had reached a steady state. The fuse wire used was No. 16 S.W.G. with a current of 96·5 amperes.

Temperature Rise inside Case			Outside of Case
At Bottom	Top	Upper Fuse Terminal	Top
20 deg. C.	34 deg. C.	70 deg. C.	20 deg. C.

intelligent use it is a fairly satisfactory material. Closer limits between safe running current and fusing current are, however, most desirable, but it is equally important that the contact should be good, and I think that rather more information on this point is required before a specification can be drafted which is based on the performance of tin wire. Various points regarding fusing currents, etc., of copper are raised in the Report, and the figures given below for copper fuses may be of interest. They refer to actual tests made with a fuse box, and in Table A is given the fusing current of various sizes of copper wire when carried in appropriate holders. It will be noted that the values are not very different from those given by Sir William Preece. Table B gives the energy loss in copper fuses of various lengths—another point that has to be considered in connection with any revision of the Rules, and Table C the temperature rise at various parts of an iron box containing eight fuses.

Mr. Charles A. Baker: I have had occasion to consider the matter of wiring artisan dwellings mainly from the point of view of getting something which must be absolutely safe and which must be reasonable in cost: the installation must be fireproof and foolproof, and I have come to the conclusion that screwed tubing is the best solution of the problem. In order to avoid going in for heavy capital expenditure, I suggest putting in—whilst the houses are being built—a skeleton screwed-tube system running from the nearest point at which the supply can be taken to a central point in the house; that would be a horizontal run; then there would be a run from the top to the bottom of the house, and the shortest possible branches of tubing to reach each of the principal rooms and the staircase. I am inclined to think that design achieves what Mr. Beauchamp referred to as a sort of ready-made system which could be fitted into all the houses of equal pattern. (I do not think it is intended to make many of these houses of identical pattern, but to some extent they must be so.) The tube might be sent on to the job cut into correct lengths, with suitable bends and boxes: there must be a plug-box near the ceiling; then lower down nearer the ground one wants a plug into which any kind of cooking or heating apparatus can be fitted, but I do not think such apparatus should form part of the original installation. If a man goes to live in a house he provides himself with a candle or a lamp or anything else. He finds in these houses of which I am speaking a conduit with an arrangement of plugs, and if he likes he can buy or hire lighting or cooking apparatus with flexible wire and plug, and easily get this apparatus connected. The important point is to put into these houses as they are built by the hundred and thousand a skeleton tube arrangement which will not cost a very large amount of money and into which can be drawn wires for any purpose required—either a small wire for lighting or a larger wire for heating—without interference with the floors and ceiling and without irritating the architect after the house is built. After a house is constructed the less one has to interfere with the builders' work the better. It has surprised me to hear various speakers talk of the chain-pull switch as something of a novelty: I have had some in my own house for a long time and recommend them. By simply giving the chain a pull the light comes on or goes off; it is a rotary switch. I believe such switches are not obtainable just at the present time, but the type should be well known. I have endeavoured to get such switches used in connection with school lighting, where the ceilings are high, 12 or 13 feet, and consequently the drop to the switch is rather

a long one, but I have never found that contractors would make any reduction on their contract price for putting in chain-pull switches instead of dropping down with conduit and wires to the usual tumbler switch. I agree with Mr. Cash that in artisan dwellings switches should be close to the lights: the fact that a man has to walk across the room to the switch is not material in a small house. I am afraid Mr. Milne will have to face the condition of putting in at least one meter. I agree that there should not be two: the average house using electricity for several purposes might very well be assessed as to the amount of energy used for lighting purposes, which would have to be paid for at, say, 6d. or 8d. per unit, and for anything beyond this assessed quantity a very much lower price should be charged, but always assuming that the actual total consumption is accurately known.

Dr. A. W. Ashton (*communicated*): One of the chief obstacles to progress in the application of electricity to the lighting of small houses is the high initial cost, i.e. of house service, supply meter, and wiring. The practice of charging a flat rate for residence lighting, entailing the installation, maintenance, and the periodical reading of a meter for each house, becomes particularly disadvantageous when applied to small cottages, in which, provided the full advantage of electric lighting is to be obtained, i.e. by the installation of lamps at all useful points, the load factor becomes so low that the running costs for energy are almost negligible compared with the stand-by charges. Experience has shown that in small houses using electricity for lighting only, not more than 400 hours' use per annum of the total lamps installed can be expected. Under these conditions the stand-by charge for energy is from three to four times the running cost, and it is more logical to apply a fixed rental per week (or per annum) based upon the total lamps installed. Such a charge can generally be included in the rent, which materially lessens the cost of collection. The meter can be dispensed with, and the cost of house services can be considerably reduced. The main difficulty in the application of such a tariff is the possibility of the consumer either (*a*) increasing the consumption of the lamps installed, or (*b*) wasting energy, by neglecting to switch off lights not required. Provided the consumer is made to understand clearly that lamps have only a certain "life," the cost of renewals will keep down the waste under (*b*) to a reasonable amount. An unauthorized increase in maximum demand can only be prevented by the installation of some form of current-limiting device. On alternating-current circuits the series condenser system offers certain advantages when applied to the lighting of small houses: (1) The demand-limiting effect is so gradual in its operation as to be barely perceptible, yet it is impossible for the circuit of a 200-volt 1-ampere condenser (for instance) to take more than 140 watts. (2) Owing to the fact that short-circuits are quite harmless, the cost of wiring can be considerably reduced without risk of fire. (3) Where mains are overloaded with lagging currents, to add connections on this system reduces the current to be carried by the cables. (4) In small cottages there are a number of points where a 25-watt lamp is too large. With a condenser a 10-watt lamp can be used. In spite of the small number of new houses built during the last five years, over 400 installations of the series condenser system have been put in operation; in nearly all cases the cost of lighting has been collected as rent.

[**Mr. Milne's** reply to the discussion on his paper will be found on page 489.]

Dundee Sub-Centre, 30 April, 1920.

Mr. H. Richardson: I propose to digress somewhat from the actual subject-matter of the paper and refer to the contract system of charging. The whole object of this tariff is to popularize electricity for every-day use and for every purpose, as we know it to-day. It would appear that it is not much good trying to popularize the use of electricity for all purposes by cheapening installations, if there are obstacles to the complete use of electricity by methods of charge, or other obstructions, intentional or unintentional, put upon the supply. It seems to me that if we adhere to the use of two separate meters for the ordinary installation, one for lighting and one for power, we shall never do much in the way of complete popularization of the use of electricity. We must get away from the old policy that there is any difference between light and power.

Mr. S. Ponsford: The author proposes to use a special wire, but in the event of a change of polarity of that wire, what will happen? The neutral wire which is uninsulated will become alive. I agree that there is not co-operation between the architect and the contractor, and in connection with artisans' houses wired under the proposed system, before a lay-out or plan can be prepared it will always be necessary to know the style of the house to be built. My impression is that if an artisan's house is built on the square system, with four or five rooms opening out of one vestibule, the matter of wiring is quite simple either in wood casing or steel tubing. I do not agree that main switches should be eliminated, but some form of combined switch and fuse would be desirable. Such apparatus is on the market at present and could be very quickly fitted. It also seems to me that some simplification of the methods of charging is necessary.

Mr. R. Kilpatrick: With regard to the installation of electric light in connection with the present housing schemes, the cost of installing such installations is only about $2\frac{1}{2}$ per cent of the cost of the complete building, so that I do not see what great gain can be made by cheapening the cost of wiring when the actual cost is such a small percentage of the total.

Mr. R. B. Mitchell: It is not only impossible nowadays to supply two meters but it is questionable whether, for these smaller consumers, we can afford even one meter at present prices. The meters of the smallest size now cost approximately £5 each, and with the revenue to be anticipated it would not pay. In these

housing schemes it would be quite impossible to have one service cable for one consumer, so long as the supply is for lighting only. The small installation does not pay at the present time, but everything is being done and will be done by most supply authorities to encourage the use of electricity for every purpose. We have in Glasgow a system of charging which, in my opinion, is as perfect as possible for the purpose. We assess flats and houses on the lighting maximum demand taken and used for a number of hours per annum, and the units registered up to the assessed amount are charged at the high rate, with a low charge for units over this amount. The year is divided into five periods, the number of units chargeable at the high rate allocated to any period being based on the number of hours of darkness in that period. The result is that the consumers usually have low-rate units in each period, and this system has the distinct advantage that the consumer pays only for the energy actually consumed. Each period stands by itself, i.e. consumers are not required to make up high-rated units not used in one period in any other period.

Mr. R. D. Archibald: I should like to ask the author whether a method could not be devised of lighting two rooms with one lamp.

Mr. J. C. Christie: This paper deals particularly with the type of house about to be built under the Government Housing Scheme. In this district it is proposed to charge a rent of from £25 to £30 per annum for one of these houses, and the class of tenant who will pay this rent is one likely to wish to have electric light. He will enter a new house with all wallpapers and decorations clean and it will be worth his while to use electric light to maintain them in that condition as long as possible. Also, the local authorities in this district are permitting these houses to be built with ceilings considerably lower than has hitherto been allowed, and for the sake of ventilation electric light will be desirable. We may take it then that the supply will be wanted, and it is important to keep down the cost so far as to make the installation possible. It is up to us, however, to see that this is not done by any methods which will endanger the soundness of the wiring, but rather by cutting out those luxuries of electric lighting which, though desirable, are not essential. Thus, plain pendants should be used throughout, and one lamp only must be provided in each room. I think the number of lamps allowed is too great for the size of house and might well be reduced from nine to six. The convenience of wall plugs must be given up, as well as such luxuries as two-way switches. We shall then get a very simple installation which should be thoroughly sound so far as it goes, and which will be moderate in price, without that cheapness being attained by doubtful methods of wiring such as flexible cables run along the roof with their usual accompanying band of black upon the ceiling, or switches on the roof operated by cords hanging down the wall. I do not approve of the use of a semi-insulated wire for the neutral. Either the wire requires to be insulated or it does not, and if it does it should be done thoroughly. I assume that the great majority of the houses wired under this scheme will be connected to public supply mains, and in most cases the use of such a semi-insulated wire would not be permitted. In the case of a direct-current three-wire system, every time that a fault to earth occurs upon one of the outers it means that the potential of the neutral wire throughout the system rises to something approaching the full working pressure, and if this cable is not thoroughly insulated there will inevitably be trouble.

Mr. D. Martin: It may be of interest to mention that in November last certain costs were worked out on actual work undertaken in widely divergent cities of the Kingdom with the following results. All the prices are per point :—

	s.	d.
London :—		
V.I.R. in screwed conduit	52	6
V.I.R. in wood casing	29	6
C.T.S. cleated up	23	3
Birmingham :—		
V.I.R. in screwed conduit	66	11
C.T.S. cleated up	52	9
Warrington :—		
V.I.R. in screwed conduit	60	0
C.T.S. cleated up	40	0
Glasgow :—		
V.I.R. in screwed conduit	42	0
C.T.S. cleated up	33	0

Since these costs were worked out, both wages and the prices of materials have advanced considerably so that I do not put them forward as current prices. They are mainly interesting from two points of view : first, they establish the claim that a first-class and inexpensive job can be carried out with cab tyre sheathed cables ; and second, the wide divergence in costs between various districts due mainly to the difference in wages rates of the workmen concerned, and the aptitude of some men to switch on to a new system more quickly than their fellows. Apart from the price there are many reasons why cab tyre sheathed cables should be used in an artisan's dwelling of the type described by the author, rather than the uninsulated outer-conductor type which he mentions. Reference has already been made to the great risks involved in the event of such an uninsulated conductor receiving the potential of one of the outers in a three-wire system, instead of being at neutral potential. With cab tyre sheathed cables such changes in polarity or potential would be of no account from that point of view. Further, there is the question of standardization to be considered. Theoretically the cable advocated by the author should cost less than one with both conductors insulated, but in practice it will cost more than the nearest standard. Regarding the prejudice against the use of cab tyre sheathed cable, this probably is due mainly to lack of experience on the part of the supply engineer and contractors, and partly to opposition from the workmen on account of the reduction in time required to install the cable.

Mr. R. A. Ure: With regard to the cost of installation, I think that the rates which the author has taken are much too low. I am also of the opinion that nothing

should be done to cheapen the wiring of an artisan's house, as the best possible type of wiring is desirable in such houses. The conditions in Scotland are a little different from those in England, as here houses are let by the month and as soon as there is a surplus of houses the new ones may be inhabited by a class of tenant who will ill-use the installation. For these reasons it is not desirable to cheapen the wiring. The total cost of the electrical installation is a small matter when we take into consideration the life of a good installation. Apart from the above remarks, the author's ideas regarding the cheapening of the wiring would not meet with the requirements of the supply companies, etc., in Scotland.

Mr. E. J. B. Lowdon : As regards semi-insulated or covered wires, I consider that for electric lighting, power, or heating there should be only two different kinds of wire used, namely, one entirely bare, run overhead in the open on insulators only, and the other insulated to pass any reasonable test. I think that semi-insulated or covered wires will only lead to trouble sooner or later, and I never use them on any installation.

[**Mr. Milne's** reply to the discussion on his paper will be found on page 489.]

North Midland Centre, at Leeds, 11 May, 1920.

Mr. T. B. Johnson : Up to the present I have been under the impression that whereas electricity is obviously the best means of lighting a house and of providing such small domestic comforts as electric heaters, irons, and vacuum cleaners, when it comes to heating, gas is so much more economical that it is difficult to justify the use of electricity. The Fuel Research Board recently published a table showing that the cost of 100,000 therms with gas at 4s. 2d. per 1,000 cubic feet was 10d., whilst with electricity at 2d. a unit it was 58d., that is approximately six times as much for electricity as for gas. No one will be better pleased than I shall be if I am wrong, but when we are called upon for our opinion we do not want to go too far in recommending heating by electricity if there is a better way. The author thinks that it is practically impossible to get people to give up the open fireplace. I hope he is mistaken, because the gain from a health point of view, by eliminating the fireplace, would be so great that it is worth a big effort to try to effect it. If, however, we cannot do without the open fireplace, it seems doubtful whether we can do without a coal-fire kitchen-range ; and if we must have the coal-fire kitchen-range, I think that is the means whereby we should get the supply of hot water. In the paper the author does not go into the cost of maintenance, but merely states the cost of current ; and I think that in some instances he has gone somewhat too far in the way of saving first cost, and that he would lose money in subsequent maintenance. For example, on page 465 he proposes to dispense with switch drops and to place a combined switch and ceiling rose on the wall near the ceiling level, operating the switch by a cord or rod attachment. If he does that, he will find that the maintenance costs will soon cancel the saving on the twin flexible, which is really not very much, although it is stated at 40 per cent. I am under the impression that this method has been tried more than once and has been abandoned because the cost of maintenance soon offset the saving in capital. On the same page the author proposes that the supply from house to house of a group should be made by means of bare overhead wires. I suggest there, too, that the initial saving would be offset by subsequent troubles in maintenance. These wires will be low, they will be at a height which will make it awkward for many vehicles to pass under them, and the wires would be interfered with either maliciously or playfully. Lastly, although we do not expect that telephone wires will be wanted on each of these houses, they would be unquestionably wanted on some, and bare telephone wires and bare electric wires do not go well together. At the top of page 466, the author suggests that a group of 12 to 20 houses should be taken, and that a common charge should be made to the occupiers of those houses, a rebate being given for economical use of the current. Good neighbourly relations could not be carried on under such a system as that.

Mr. W. H. Wraith : I certainly think that the idea on page 466 of having groups of consumers would lead to economy and ought to be applied. I do not agree, however, that an extra charge should be made for small industrial apparatus. An electric iron usually takes only a very small current, and the charge for nine lights could easily allow for the extra current. I am not in favour of electric heating, and I do not find it as cheap as a fire.

Mr. G. F. Davidson : The cost of wiring with twin wires for a heating plug is given by the author as about 18s. The cost of a moderately good combined switch plug to-day, without any wiring, is, however, in the region of 18s. I do not know how the author has arrived at the costs stated in the paper. I also do not agree with this cost of a lighting installation. Only last week-end I had to estimate for 500 houses on one estate. The installations were to be carried out in screwed tube, with C.M.A. cable, complete with opal shades and lamps, and the lowest possible prices worked out as follows : For a 7-light house, lighting only, £22 5s. ; 8 lights, £25 10s. ; 8 lights in blocks of four, £29 10s. per house. The variation in those prices is due to the cost of 7/16 S.W.G. interconnecting mains. The supply authority proposes to put in one service for each pair of houses, and one service for blocks of four, and it is suggested to interconnect inside by 7/16 S.W.G. mains. In blocks of four this increases the cost to my mind rather unduly, on account of the arrangement of the end house. The internal runs are rather longer and more costly. Cleat wiring I do not agree with at all. I think that after the houses have been occupied about a week the wires in the kitchen will be used for hanging up clothes. I am sure that the cost of repairs to those houses with cleat wiring would be very much more than if a good job were made in the first case. The lamps should be fairly high, and probably in the living

room should be suspended by a tube rather than by a flexible cord. I think 1/18 S.W.G. or 3/32 S.W.G. is quite small enough, and I do not agree at all with the author's suggestions regarding the use of uninsulated wires. I think it is very desirable that there should be a separate meter for each house. I would encourage people to use special apparatus such as washing machines, irons, and so on. I do not see why there should be any difficulty in charging for the current without putting in two meters. Why should not supply authorities put a card in front of each meter stating that "You are entitled to so many units per quarter at such and such a rate; if you exceed that number of units, you will be charged at a lower or special rate"? It is very desirable to fix a very good type of switch, which should be earthed. I do not find that many switches are earthed, and in one or two instances, especially with steel-framed concrete houses, there have already been one or two nasty accidents. More attention should be paid to this matter. The average cost of a house is something like £1,000, and if £20 to £25 of that is spent on electric lighting it is a very low figure and would never be considered after the first installation was put in. The heating problem I agree is very difficult, and as far as I can see at the present time electrical heating will not be applied to artisan houses, at any rate in the north. With regard to cooking, the cost of an electric oven with hot-plates is to-day considerably higher than the cost of the chimneys in the house, which the author gives as £25 per house. I agree, however, that the cost of electric cooking apparatus ought to be very considerably reduced.

Mr. H. Moss: On looking at the costs from the contractor's point of view, I cannot see how with present prices a house could be wired at £14 in close-joint tubes with continuity fittings. Whilst I should very much like to see a cheaper method of wiring adopted I do not see at the moment how we are going to do it. I have been a strong advocate for some years of trying to get cheap installations for private houses, and I must differ from some previous speakers, inasmuch as I consider that overhead mains are highly satisfactory for distribution from house to house when blocks of buildings are being put up together; and it is far cheaper than to run supply mains through basements in a row of houses. I have been connected with installations where we have adopted overhead mains, and it has been the means of cheapening the cost considerably. In the smaller class of houses I do not see why we should not have aerial wires run on insulators. I would not go so far as to fix them to the chimneys, because I think they could be put out of the way by running on the backs of the houses where they would also be far more out of sight. A case I have in mind is not many miles from Leeds, where there are also telephone wires. There has been an electric supply for the last 10 years, and I have never heard of any difficulty arising through the telephone wires coming in contact with the lighting wires. So far as the service is concerned, I strongly advocate aerial wires where unsightliness has not to be considered too much, and those wires I should like to see run at the backs of the streets, and not the front. I think it is only fair that every consumer should pay for what he uses, and every consumer should therefore have a meter. The cost of meters to-day is rather prohibitive, and the rentals are sometimes rather heavy; but numbers of consumers would, if they had the chance, buy their meters outright rather than pay the rental year after year. Where a consumer is prepared to buy the meter, I do not see why he should not be allowed to do so, provided that it is sealed by the supply authority and no one has access to it except the supply authority's inspectors. The grouping of consumers would be satisfactory only if each used approximately the same amount of light and each had installed the same number of irons, cookers, radiators, etc. Regarding the author's suggestion about a cheap method of wiring with a twin wire, I should like to know if any of this work has been carried out under present conditions. When he suggests that a 9-light installation could be put in for £7, i.e. at an average cost of 16s. 9d. per light, and that radiator plugs should be put in for 18s. per point, I fail to see what kind of radiators he proposes to use, as it is impossible at present to put a radiator circuit in for that figure with any kind of wiring and with suitable flexible cable, switches and fuses that would pass the rules and regulations of any supply authority. £5 per plug is a common price to-day for radiator plugs in houses, and I do not see how we can reduce it to 18s. per point. I think it is always policy to have every radiator plug on separate fuses, which means a separate pair of wires from a fuse board into every room. In conclusion I am afraid we shall be a long time before we get electricity adopted universally for heating and cooking in artisans' dwellings.

Mr. H. Adams: The author has compared the cost of an electrical installation with the present cost of building. Would it not be better to take the cost of an electric installation compared with the cost of a gas installation? He also suggests replacing the main switch by fuses. Assume that we have only a pair of fuses. If either of these fuses blow, the whole of the house would be in darkness; I therefore suggest that two sets of fuses would be preferable. If twin wire be used, it will undoubtedly result in a lot of waste if the ceiling rose and the switch are not placed together, as the author suggests; and as it is the general practice to have the switch at the door, to enable the light to be switched on when entering the room, I think the additional cost in wiring is fully warranted. Cleat wiring will undoubtedly save expense, but no matter how neatly it is done, it will at some time or other become unsightly, especially when the rooms are papered. Moreover, if the wall is distempered it will not do the wire any good, especially if only braiding is used as a protection. The author mentions on page 465 that there is a possibility of electrolytic action, and he has made allowances for that by having a $\frac{3}{8}$ inch insulating tube. At that rate, this possibility will also be present wherever the wiring is in contact with the building. Co-operation with the architects in building is a point worthy of consideration, and if the runs could be fixed during building operations and wood plugs placed in suitable positions, a great saving would be effected. As regards the method of leading in wires, the overhead proposal has great weaknesses, in the way of faults

and leakage. There will be excessive leakage in wet weather and during snow unless very good insulators are used, and double-shed insulators are rather expensive. Would it not be better to have some system of block wiring, similar to that which the Post Office uses at the present time in large buildings ? The supply is brought to a pothead outside, and from this branches are taken to the various offices. It would be quite a neat arrangement, and preferable to open work. The flat-rate system would undoubtedly lead to extravagance, but, on the other hand, would it not be possible for each article which consumes more than an ordinary 60-watt lamp to be registered before it is sold, and these certificates to be sent to the supply authorities ? If we had a flat rate, it would, as the author suggests, act as a stimulus for the sale of electrical apparatus and the use of the same. On page 465, it is stated that £25 per house would be saved by the omission of chimneys. This saving alone warrants consideration and would allow for a first-class electric light installation for an ordinary house. With regard to the airing cupboard, the type of artisan's house which I have seen is very small and I do not think there would be space for a cupboard. To sum up, I should undoubtedly recommend a good class installation using light grip tubing and well-insulated wire, as the extra initial cost would be more than covered by the saving effected in subsequent repairs. Another most important point for the contractor to watch is the efficiency of all electrical apparatus, as upon this the future development, or I should say the future use of electricity by the householder depends.

Mr. A. Pickersgill : I am interested in the wiring of artisans' dwellings. Cleckheaton Council expect to put up 300 houses on the garden city plan. The surveyor asked me to get out details of the electrical devices. I have done that so far as I could from his plans, but the question of wiring the houses and how the service is to be run was rather a moot point. I considered the possibility of taking the cables through the chimney tops, as at Felixstowe. It did not seem to me to be a feasible proposition so far as our area was concerned, owing to the sulphur and acids in the air from the galvanizing works and dye works. The wires would soon be corroded and the service would collapse. We also studied the possibility of erecting a pole at the end of each block of houses and of going through the under-drawings. This would not be done without being unsightly, and we therefore decided to run a separate service into each block of houses. To me the sole point about wiring is not the cost or quality of the material, but the workman. One contractor quoted me £5 a light for about 40 lights in a motor garage, and I got another man to do it for 32s. per light with twin lead-covered wire and it was a good job too. Contractors do not look after their men, and owing to ca' canny they do not get through the job. That is why the cost of wiring artisans' dwellings, mills and workshops is prohibitive. During the last five months I have connected more consumers to my mains owing to getting some competition in the town than I have done in six years.

Mr. S. B. Reid : As I am connected with the housing scheme at Morley, I am fully alive to the fact that electric lighting, for the houses of the working classes, will not generally be adopted until it compares in initial cost favourably with gas installations. This question should be considered very carefully by electrical contractors, and if rigorous economy be practised to reduce the first cost there will be no difficulty in displacing gas, and I have no doubt that the Housing Commissioner would welcome this. The Commissioner is compelled to exercise economy in every possible direction, and many schemes have been delayed owing to high tenders. In the Morley Housing Scheme the tender per house for a 7-point gas installation is £12, exclusive of mantles and shades. To effect economy in wiring I propose to use bare overhead conductors supported on insulators close to the eaves, which are about 15 ft. 6 in. above the ground line. The conductors will be tapped at the centre of each house and the external insulated cables on cleats will be carried down the walls to the first floor-level, where they are led into the house at a point just below the ground-floor ceiling, thence to the meter and replacement fuses. Insulated cables are carried into the under-drawing and radiate to the various ceiling roses for lights on the ground floor, while the bedroom lights are coupled to the nearest cables in the under-drawing by means of insulated cables which are protected in tubes or casing where exposed, and run up the wall to the lamp bracket. All lampholders are to be provided with a key switch. In the case of the principal bedrooms a combined dimmer and switch may with advantage displace the key switch lampholder, the ordinary lampholder being substituted. The dimmer should be fixed just below the bracket. Returning to the outside conductors, these may be supported on insulators on the various blocks of buildings. The conductors would be well out of reach and completely obscured by the trees on the verges of the streets. In the most fashionable parts of Calcutta, " the City of Palaces," bare overhead conductors are carried from the streets to the buildings without impairing the architectural features. Some years ago I installed a combined ceiling rose and switch operated by means of cords. This was a complete failure, and as an alternative a rod with a hook attachment was substituted, much to the discomfort of all parties concerned. Finally the whole building was re-wired in the usual way. Regarding the saving effected by eliminating fireplaces and chimneys, I do not agree with the author. In the present housing schemes a good supply of hot water is ensured from fire-back boilers, and considerable improvements would have to be made before this is accomplished by electric geysers suitable for artisan dwellings. Gas-heated geysers are also very unsatisfactory. The author refers to a pilot burner, but there are some types without pilot burners ; these are undoubtedly more economical in gas consumption, in addition to facilitating inspection and repairs. Seventy-five cubic feet of gas per geyser corresponds to the guarantee given by some well-known makers, the calorific value being 630 therms per cubic foot of gas. Recent quotations for gas-heated geysers are in the neighbourhood of £60, and anything approaching this figure for a geyser would not

be entertained by the Housing Commissioner. With regard to electrical cooking, I do not think such appliances would appeal to the average artisan. He would prefer the ordinary cooking range with a coal fire. The artisan must be gradually educated to the uses to which electricity can be put. Give him electric light first; he will ask for the other appliances as soon as he sees their utility. Electrical cooking appliances that I installed at Calcutta and in other important towns proved very successful, but it was amongst the better class of people who readily appreciated the advantages arising from the use of such appliances. With reference to fires caused by cleat wiring, this is not possible when the wires are properly installed. A number of buildings were equipped at Calcutta on the cleat wiring system with considerable success and at a reduced cost. Not a single case of fire was reported in any of these installations, whilst I do know of cases where fires have been caused in the enclosed systems due to careless workmanship. In conclusion, I am in agreement with the author respecting economic wiring of houses for the working classes.

Mr. L. Jessop: With regard to the author's suggestion to use combined switches and ceiling roses, or the separate articles fixed on one block, I think this is quite all right. I have fixed some thousands of them in factories and have a great number under maintenance at the present time. I find that these switches will last four or five years without any maintenance being required. The type used is the usual "Wandsworth" or "Tucker" fish-tail with a couple of chains attached; in addition, I fix an extra chain to carry the weight of the shade and lamp and I do not see any objection to using similar methods in an artisan's dwelling. I do not think that this is the time to go in for all the luxuries that are attendant on electricity supply. In an artisan's dwelling it is necessary to provide an installation of electric light as cheaply as possible. The householder has been accustomed to go to the gas and turn on a tap; relieve him of the necessity of providing a match, but leave the tap, and I think we can make a good job there. With regard to the author's suggestion of co-operation between the architect, builder, and electrician, so that wood fixing-blocks would be built in by the builder, I do not think electrical contractors would find that it would cheapen installations, because the architect would make it a condition in his contract that as the building was in progress the electrical contractor would have to keep his man in attendance to put in the fixing-blocks and be responsible for their accuracy. With regard to metering of current, there is one system which has not been dealt with by the author, and that is the lighting of artisans' dwellings from alternating-current supply, using a condenser for limiting the current. I have had the opportunity of inspecting some houses which have been done on that system, and with a charge of 6d. per week the company supplying electricity make a profit. The houses have five or six lights, with 50-c.p. lamps in the living rooms and 30-c.p. lamps in the bedrooms, which is similar to what is provided by the ordinary incandescent gas burners. In those houses a considerable saving in the cost of wiring was effected, and also a very considerable saving due to the absence of meters, meter readers, and inspectors. The wiring is carried out almost entirely with single cables, all lamps being in series. Instead of being switched out in the usual way the lamps are short-circuited. A good quality wire can be used and the cost of seven lights, including a condenser, and reasonable shades and lamps, would not exceed £10 10s. In the case of a direct-current supply I do not see why a reasonable current-limiter should not be used instead of a meter. In an artisan's house the tenant does not require the whole of the house lighting at one time; two lights will probably be the utmost required. Therefore if a current-limiter be installed which will limit the supply, say, to two 50-c.p. or one 50-c.p. and two 25-c.p. lamps, that would, I think, be quite sufficient. By adopting this method we do away with the cost of meters and inspection and also, in the case of alternating-current supply, the necessity of fuses on the secondary side of the condenser. If a lampholder is short-circuited, nothing happens.

Mr. W. W. Firth: I should like to support the remarks which have been made regarding the comparative cost of electricity and gas and the question of the Health Commissioner or Building Commissioner. In Dewsbury at the present time the building of probably 200 houses is being considered, and we have come on the scene after the prices have been fixed. The only thing we can compete against is 12s. 6d. per point for gas. That has not only been cut down by the Commissioner, but agreed to by the plumbers. I think that until the Institution deals far more directly with the Health Commissioners in the sense of trying to impress upon them the fact that there are other points besides first cost, it is not much use going into the question of cost, because the lowest figure given by the author comes out at about 25s. per light. We have been told by the Borough Surveyor's Department that unless we can bring our price down to 12s. 6d. it is no use. That is the maximum cost which he is allowed, and he has to get the cheapest lighting he can.

Mr. L. Milne (*in reply, communicated*): Several speakers have drawn attention to the omission of any estimate of the cost of wiring on the Henley, Stannos and Kaleeco systems, etc. The estimates on page 464 were given for comparison only, and I purposely refrained from giving comparative estimates of systems in which there may be proprietary rights, although I am fully aware of the many advantages which some of these systems possess.

Mr. Cross and some other speakers consider the estimates given on page 465 to be optimistically low. All the estimates given were formed on exactly the same basis, providing the same percentage for contractors' establishment charges and profit. On examining Mr. Cross's figures I am inclined to think he has taken to-day's prices for the articles he enumerates, and has deducted these from estimates which are based on prices ruling in the autumn of 1919. The percentage saving in cost of hard wires and flexibles of the types suggested are based, not on theoretical considerations, but on actual quotations from an important member of the Cable Makers' Association.

Many speakers raise objections to any form of cleat wiring and point out that the housewife may use these wires for attaching a clothes line, etc. Should this be done, nothing very serious will happen beyond inconvenience to the housewife from a probable interruption of the supply. It is much easier to tie a clothes line between two flexible pendants, within convenient hand reach, than to climb up to the ceiling to tie a line on to the cleated wires, and yet I do not find the suggestion made that flexible pendants should be abolished because clothes lines may be tied to them.

Mr. Beauchamp says we must have propaganda. Mr. Cash says we must have reduction in costs. Surely we must have both. We cannot have too much propaganda; but propaganda will be enormously assisted if instead of approaching a local authority with a proposition to provide all the admitted advantages of an electrically equipped home at an additional cost of, say, £30 a house, we can offer all these advantages and in addition a saving in the total cost of building. I am convinced that we can do this.

Mr. Cash suggests cleat wiring under floors. A large amount of this class of work has been done in permanent buildings by the War Department at Aldershot. So long as the wires run parallel with the joists it is cheap, but it ceases to be cheap when holes have to be bored in the centre of the joists *in situ* for transverse runs.

I agree with Mr. Cross that the figure given for consumption of current for electric cooking is probably high, but as our experience of electric cooking in artisan dwellings is at present limited, I intentionally gave a conservative figure.

I am surprised that no member has been able to suggest any case of the coincidence of an outbreak of fire and the development of a fault on a distribution system. This confirms my argument that slight insulation only on the neutral wire is sufficient.

Mr. Ponsford raises the question: What will happen in the event of a change of polarity? By reason of the large number of undiscovered faults now existing on the neutral side, this is a real danger at the present time, and will be diminished rather than increased when station engineers know they cannot rely on the insulation of the neutral side and take proper precautions to guard against an accidental change-over. The nearest approach I can find to such coincidence as I have been seeking occurred in the manner Mr. Ponsford suggests. Accidentally the neutral in a section of a three-wire distribution was connected to an outer and at the same time a fire developed in a building on this section.

The case cited by Mr. Cross where under normal conditions a pressure of 50 volts existed between the neutral wire and earth is, I imagine, of the rarest occurrence and should, I think, be met rather by the improvement of the system of supply than by the condemnation of the suggested system of wiring. A difference of pressure between the neutral and earth lower than what is sufficient to maintain an arc involves, I believe, no fire risk.

Mr. Berry's suggestion of a communal supply of hot water is of much interest and, from an economic point of view, is, I think, sound. It is, however, open to the same objection as is raised to the metering of houses collectively, viz. the individualistic prejudices of the people.

With regard to bare overhead services, the best position for these depends on the design of the houses; in some cases it will be on the chimneys, in others under the eaves, and again in others through the houses themselves. The point I would emphasize is, that the electrical engineer should be consulted at an early stage and not left to find the best way after the houses are designed and built. As to maintenance, my experience is that the cost of repairs on overhead services is lower than on underground services; although repairs are required rather more frequently, the cost of each repair is markedly less.

Mr. Baker states that he has not found any contractor who would reduce his contract price by substituting chain-pull switches for switches at hand-level. He himself gives the reason in a preceding sentence, namely, the difficulty existing until recently in obtaining these switches. Dispensing with switch-drops effects a larger saving than any one of the other economies I have suggested, and when there is a demand in large quantities for these combined chain-pull switches and ceiling roses, it will doubtless be met. In the meantime, an effective substitute is available by the use of a separate ceiling rose and tumbler switch with chain or rod attachment.

It is not contended that the suggestions made will give an electrical installation of the same quality as when carried out in solid drawn steel tube with an ample provision of draw-in and inspection boxes. The practical question before us is not what is absolutely the best method of wiring a small house, but whether we shall install a cheap yet efficient electric installation or allow these houses to be lighted by gas or paraffin lamps.

With this alternative before us, I should unhesitatingly give the preference to a cheap but efficient electrical installation on the grounds of convenience, health, and immunity from fire risk. An electrical installation is, in the nature of things, so free from fire risk that electrical engineers have, I feel, made somewhat a fetish of this point. If we were asked to install such a dangerous piece of apparatus as a paraffin lamp we should hold up our hands in horror and insist that such a dangerous thing should be securely screwed to the floor so that it should not be knocked over, and even then we should probably ask that the apparatus should be fitted with a fire extinguisher in case the bowl of the lamp should burst.

Although I would in no way minimize the importance of fire risk, I would strongly urge that the practical alternatives open, with prices as they stand to-day, are a cheap electrical installation, or lighting by gas or paraffin lamps, involving a far greater fire risk.

ALTERNATING-CURRENT TRACK CIRCUITING.*

By L. H. PETER, Associate Member.

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SUMMARY.

(1) The distinction between "in phase" and "quadrature" relays.
(2) The reasons for adopting the non-inductive shunt value in this paper.
(3) The vector diagrams of a track circuit without impedance bonds, and the phase displacement obtained with two types of relays.
(4) The vector diagrams of a track circuit with non-resonated impedance bonds, and the phase displacement obtained with two types of relays.
(5) The vector diagrams of a track circuit with resonated impedance bonds, and the phase displacement obtained with two types of relays.
(6) The effect of introducing the relay transformer into the track circuit, and the diagrams referring to this.
(7) A method of varying the relay track winding power factor, and the effect on the vector diagram.
(8) A method of feeding the track circuit using capacity and inductance in series and varying the power factor of the current supplied to the track.
(9) The phase displacement at various points in a track circuit as shown by the phase-meter.
(10) The protection of relay transformers against direct-current soaking.
(11) The impedance bond, non-resonated and resonated, its characteristics and the effects of direct-current unbalancing with various air-gaps.
(12) Effect of direct current superimposed on alternating-current relays.

The methods of applying alternating current to track circuits have already been described in the technical Press of this and other countries, and it is not the author's intention to deal with the application but rather with the factors that must be taken into account when deciding on the apparatus to be used. The apparatus forming a track circuit of the simplest kind may be considered as comprising a transformer or other method of supply, a regulating device for adjusting the supply and a relay. The alternating-current relay has been developed considerably during the last few years, and it is now usual to use a track relay in which a large proportion of the power required to operate the relay is supplied locally and only a small portion is supplied from the track circuit. These relays are commonly known as "two-element" relays, as distinct from "single element" relays in which the whole of the power required to operate the relay is taken from the track circuit. The single-element alternating-current track relay has suffered from the disadvantage of its heavy current consumption, and although it is still of great value for short track circuits, this has not been held sufficient to justify more than a reference to it at the present time. The two-element relay has been almost universally used for medium and long track circuits, and it has therefore been adopted in each of the hypothetical track circuits shown in Figs. 3 to 20.

To include the whole of the two-element relay class it has been necessary to distinguish between those relays which are designed to operate with the currents in the two elements in phase or 180° out of phase with one another, and those relays which are designed to operate with the currents in the two elements in "quadrature." These relays are hereafter referred to as "in phase" and "quadrature" relays respectively.

It is only by carefully choosing the relay, impedance bonds and method of feeding the track circuit, with a view to the operation of all three parts as a combination, that the best results will be obtained. If we consider a few cases, each with a different combination of relay and impedance bonds, this will be clear. For the purpose of illustrating the good and bad combinations of relays and impedance bonds, the vector diagrams in Figs. 3 to 20 have been drawn with the "in phase" and "quadrature" operating values of the relays used, and the corrected values for the relays operating at the phase angles shown on the various diagrams have been omitted to avoid complication. Those who wish to obtain the corrected relay-operating values at any phase displacement can do so by the graphical method shown in Fig. 1. Method (*a*) is applicable to "in phase" relays and method (*b*) to "quadrature" relays. Two types of impedance bonds are also referred to: the ordinary form of bond consisting of an iron core and a two coil winding, and the resonated impedance bond in which an additional winding and condenser are added to increase the impedance of the bond. The "distributed leak" method has been adopted for purposes of showing vectorially the electrical state of each track circuit, as this method, although not as accurate as that using hyperbolic functions, is the one more generally used and understood.

The vector diagrams of the tracks shunted at the transformer end of the track have been drawn to show a unity power factor shunt. Various statements have been made as the result of experiments and calculations regarding the power factor of the train shunt, and some explanation is due for adopting the non-inductive shunt for these diagrams. If the shunt circuit formed by a pair of wheels joined by an axle and standing on

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the track is considered, it may be regarded as consisting of three parts:

(*a*) The contact resistance from the rail to one wheel.
(*b*) The inductive circuit formed by the axle and two wheels.
(*c*) The contact resistance from the second wheel to the second rail.

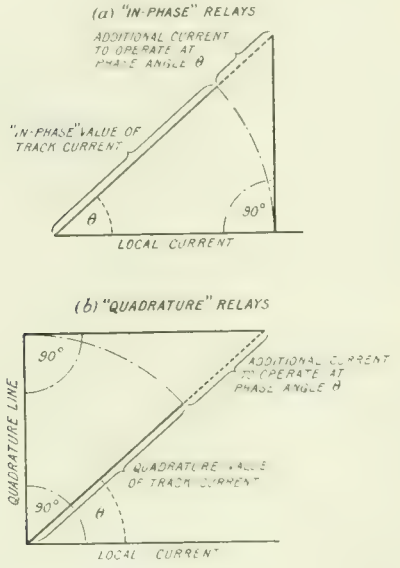

FIG. 1.—Method of correcting relay operating figures for phase displacement.

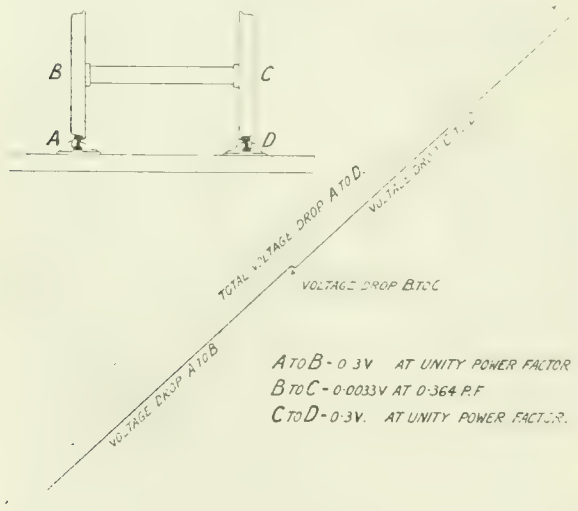
B
C
A
D
TOTAL VOLTAGE DROP A TO D.
VOLTAGE DROP B TO C
VOLTAGE DROP A TO B
A TO B - 0·3V AT UNITY POWER FACTOR
B TO C - 0·0033V AT 0·364 P.F.
C TO D - 0·3V. AT UNITY POWER FACTOR.

FIG. 2.—Diagram to show voltage drop across shunt formed by wheels and axle.

(*a*) and (*c*) are non-inductive; (*b*) is inductive and, owing to the half loop formed by the wheels and axle and the skin effect of both these, it may have a comparatively low power factor. Tests made, however, have shown that the contact resistance between rail and wheel is many times the impedance between wheel and wheel and we therefore have a series circuit with two high resistances in series with a small inductance, the net result of which is to give a circuit that for all practical purposes may be taken as non-inductive. This is still more the case when the rail and wheel contact resistance increases to a value which would be commensurate with the shunting-out value of the relay, as the contact resistance, which is non-inductive, will then be so many times greater than the small impedance between wheels that the latter may be neglected and the shunt-circuit power factor taken as unity.

Let us take a concrete case at 60 cycles, which may be considered to be the highest frequency in general use for signal track-circuits. The following figures are quoted from the results of tests published by Mr. H. McCready in the United States:—

Supply	Total Weight in lb on Track	Amperes, Axle Current	Volts across Rails	Impedance
A.C. 60 cycles	18,700	112·5	0·12	0·0011
D.C... ..	18,700	55	0·022	0·0004

$$\text{Power factor} = \frac{0\cdot0004}{0\cdot0011} = 0\cdot364.$$

If now the contact resistance between wheels and rails rises to a point where it might concern the shunting out of the relay, say 0·2 ohm, and if the shunt current is in the neighbourhood of 3 amperes, the vector diagram would be as follows:—

Drop from rail A to first wheel B = 3 × 0·1 = 0·3 volt. P.F. = 1·0.
Drop from wheel B to wheel C via axle = 3 × 0·0011 = 0·0033 volt. P.F. = 0·364.
Drop from wheel C to rail D = 3 × 0·1 = 0·3 volt. P.F. = 1·0.

It will be seen from Fig. 2 that the vectorial sum of these three quantities is so close to the straight line that the resultant line may be considered to be of unity power factor for all practical purposes.

Taking first the simplest form of alternating-current track circuit in which one rail is given up wholly for signalling purposes. The electrical state of such a track circuit with an "in phase" relay is that shown in Fig. 3 when the track is clear, and as shown in Fig. 4 when the track is shunted by the maximum train shunt at the transformer end. It will be noted in Fig. 3 that the relay is operating with the track current 32° displaced in phase from the local current, and we must therefore divide the "in phase" operating values by the cosine of 32° to get the correct operating values with this phase displacement.

When the track is shunted by the application of a non-inductive train shunt (resistance 1·4 ohms) at the transformer end, the phase displacement between track and local currents is reduced to 23°, and the release values for the relay will accordingly be the "in phase" release values divided by the cosine of 23°.

These diagrams have been constructed to show a thermal resistance between the track transformer secondary and the rails, this resistance being so adjusted that the total current output from the transformer to the track may be said to remain constant whether the track is occupied or not.

Fig. 21 shows the values of such a resistance and it will be noted that with a pressure-rise across the resistance from 4·76 volts in Fig. 3 to the 5·46 volts shown in Fig. 4, the current increase would be practically nil, as we should be working on the flat portion of the curve.

If we substitute for this thermal resistance a resistance of the ordinary type to obtain an equal shunt, we must so arrange the track circuit that with the track clear a very high percentage of the transformer voltage is lost on the resistance in order that the current increase when the track is shunted may not be appreciable. Alternative methods which have been used to prevent this increase of current when the track is shunted include the use of a constant-current transformer and inductances in which the iron is worked well below the "knee" of the saturation curve when the track is clear. Both these methods, however, are less efficient from the point of current consumption than the one shown. A further method of feeding the track circuit with a capacity and an inductance in series has been tried and the results obtained by using this method are given later in this paper.

Returning to Figs. 3 and 4 in which we have single-rail track circuits with "in phase" relays it will be noted that the relay track current vector is comparatively large, and it is obvious that if we can increase the relay impedance and also reduce the volt-amperes required for it from the track, we shall greatly improve the shunt value. Such a case is shown in Figs. 5 and

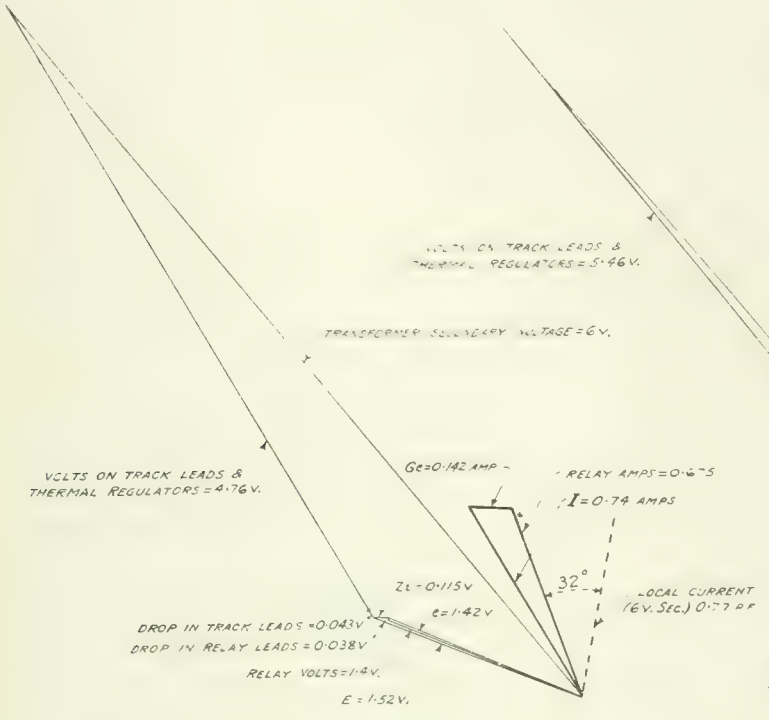
VOLTS ON TRACK LEADS & THERMAL REGULATORS = 4·76 V.
Ge = 0·142 AMP.
RELAY AMPS = 0·675
I = 0·74 AMPS
32°
Zl = 0·115 V
e = 1·42 V
LOCAL CURRENT (6 V. SEC.) 0·77 PF
DROP IN TRACK LEADS = 0·043 V
DROP IN RELAY LEADS = 0·038 V
RELAY VOLTS = 1·4 V.
E = 1·52 V.

Fig. 3.—Single rail track without impedance bonds, with a resistance in feed, and galvanometer relay. Supply, $33\frac{1}{3}$ cycles. Track circuit, 1,000 ft. long. (Track clear.)

Galvo. Relay: Local 50 v. 0·36 amp. 0·72 P.F.
Track 1·4 v. 0·675 amp. 0·72 P.F.
Rail Impedance, Z, 0·1711 ohm per 1,000 ft. at 0·300 P.F.
Track Conductance, G. Ballast Res. 10 ohms per 1,000 ft.
∴ G = 0·1 per 1,000 ft.
Relay to be 15 ft. from track. 30 ft. of 7·22.
Res. of relay leads $\frac{1·93}{1,000} \times 30 = 0·058$ ohm.
Drop in relay leads = 0·058 × 0·675 = 0·038 v.
Volts on track, relay end, e = 1·4 + 0·038 = 1·42 v.
Amperes on track relay end, I = 0·675 amp.
Total amps., I = 0·675 + 0·142 = 0·74 amp.
Track leads 15 ft. long. (30 ft. of 7·22.) Res. 0·058 ohm.
Drop in track leads, 0·058 × 0·74 = 0·0420 v.
Total volts, E = 1·4 + 0·038 + 0·115 = 1·52 v.

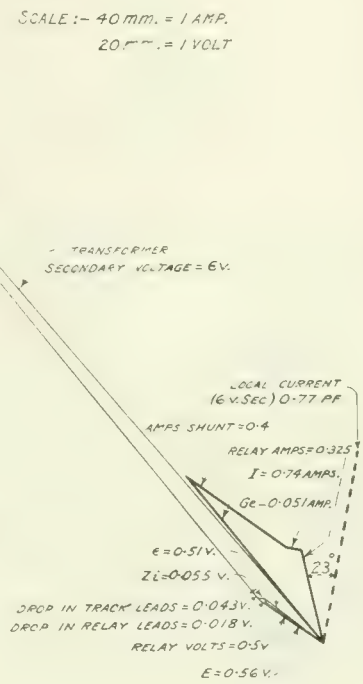
SCALE:- 40 mm. = 1 AMP.
20 mm. = 1 VOLT
VOLTS ON TRACK LEADS & THERMAL REGULATORS = 5·46 V.
TRANSFORMER SECONDARY VOLTAGE = 6 V.
LOCAL CURRENT (6 V. SEC.) 0·77 PF
AMPS SHUNT = 0·4
RELAY AMPS = 0·325
I = 0·74 AMPS.
Ge = 0·051 AMP.
23°
e = 0·51 V.
Zl = 0·055 V.
DROP IN TRACK LEADS = 0·043 V.
DROP IN RELAY LEADS = 0·018 V.
RELAY VOLTS = 0·5 V
E = 0·56 V.

Fig. 4.—Train shunt at transformer end of track.

Relay release figures 0·5 v. 0·325 amp. 0·77 P.F.
Rail Impedance and Track Conductance as in Fig. 3.
Drop in relay leads 0·058 × 0·325 = 0·018 v.
Shunt amps., 0·4 amp.
∴ Resistance of shunt = $\frac{0·56}{0·4}$ = 1·4 ohms

6, which represent a quadrature relay operating on the same track circuit as in Figs. 3 and 4 but at a higher frequency. The same type of resistance is shown in

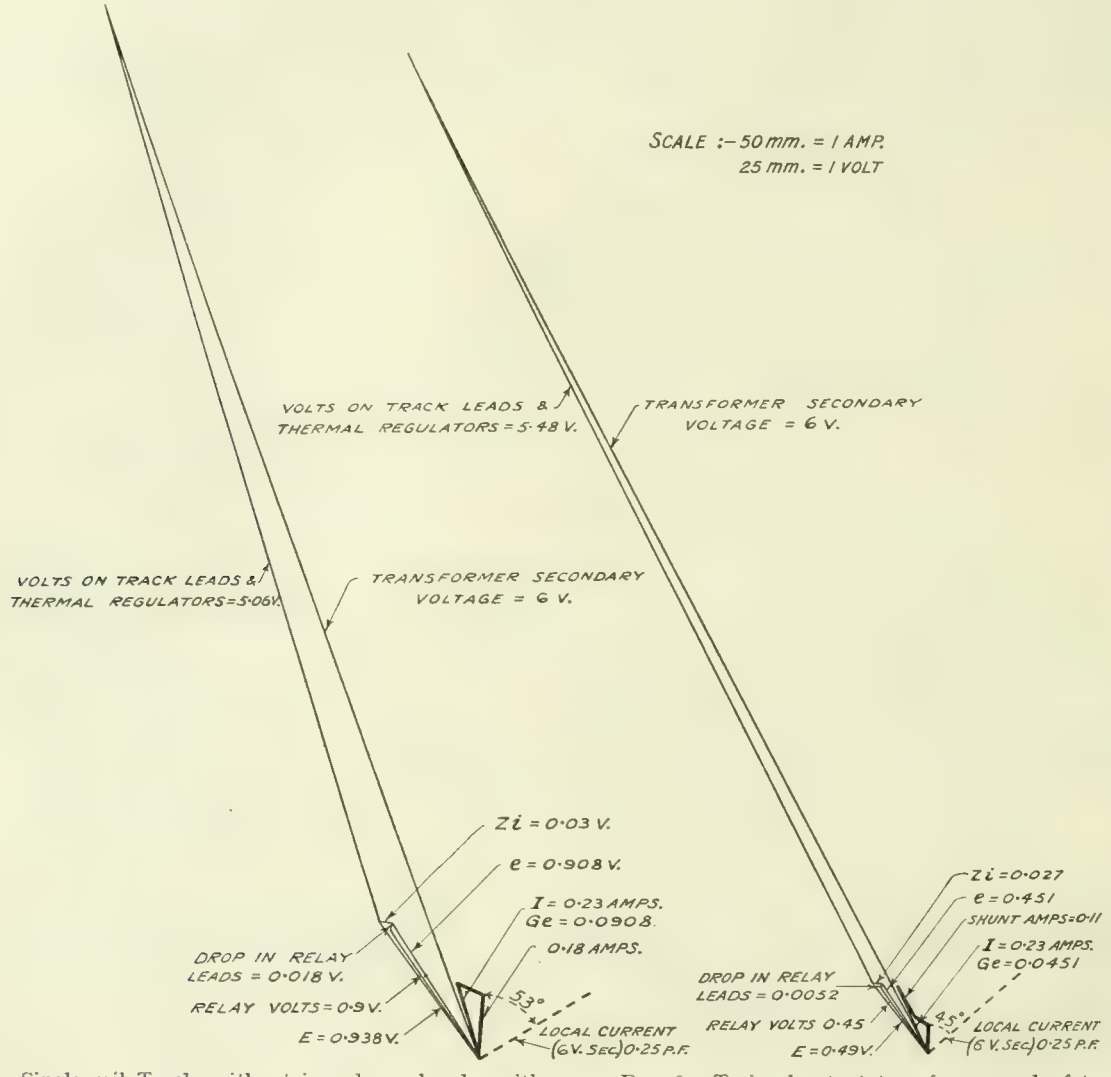
SCALE :- 50 mm. = 1 AMP.
25 mm. = 1 VOLT
VOLTS ON TRACK LEADS & THERMAL REGULATORS = 5·48 V.
TRANSFORMER SECONDARY VOLTAGE = 6 V.
VOLTS ON TRACK LEADS & THERMAL REGULATORS = 5·06 V.
TRANSFORMER SECONDARY VOLTAGE = 6 V.
Zi = 0·03 V.
e = 0·908 V.
I = 0·23 AMPS.
Ge = 0·0908.
0·18 AMPS.
DROP IN RELAY LEADS = 0·018 V.
RELAY VOLTS = 0·9 V.
E = 0·938 V.
53°
LOCAL CURRENT
(6 V. SEC) 0·25 P.F.
Zi = 0·027
e = 0·451
SHUNT AMPS = 0·11
I = 0·23 AMPS.
Ge = 0·0451
DROP IN RELAY LEADS = 0·0052
RELAY VOLTS 0·45
E = 0·49 V.
45°
LOCAL CURRENT
(6 V. SEC) 0·25 P.F.

FIG. 5.—Single rail Track, without impedance bonds, with a resistance in feed, and two-element vane relay. Supply, 50 cycles. Track circuit, 1,000 ft. long. (Track clear.)

Relay, Two-element Vane. Local 100 v. 0·44 amp. 0·25 P.F.
Track 0·9 v. 0·18 amp. 0·8 P.F.
Rail Impedance, Z, 0·3 per 1,000 ft. at 0·5 P.F.
Track Conductance. Ballast Res. 10 ohms per 1,000 ft.
$\therefore$ G = 0·1.
Relay to be 15 ft. from track. 30 ft. of 7/22.
Res. of leads $\frac{1·93}{1,000} \times 30 = 0·058$ ohm.
Drop in relay leads = 0·058 × 0·18 = 0·01 v.
Volts on track, relay end, $e = 0·9 + 0·01 = 0·908$ v.
Amperes on track, relay end, $i = 0·18$ amp.
Total amps., I = 0·18 + 0·0908 = 0·23 amp.
Total volts, E = 0·9 + 0·01 + 0·03 = 0·95 v.
Track leads 15 ft. long. 30 ft. of 7/22.
Res. of leads, 0·058 ohm.
Drop in track leads = 0·058 × 0·23 = 0·015 v.

FIG. 6.—Train shunt at transformer end of track.

Relay release figures, 0·45 v. 0·09 amp. 0·8 P.F.
Rail Impedance and Track Conductance as above.
Drop in relay leads, 0·058 = 0·09 = 0·00522 v.
Shunt amps. = 0·11 amp.
$\therefore$ Resistance of shunt $= \frac{0·49}{0·11} = 4·45$ ohms.

the feed circuit, but the angle between the track and local currents is only 53° instead of the 90° required to give the best operating figures on the relay. The shunt in this case is 4·45 ohms at the transformer end, although the relay release figures are not a much higher percentage of the operating figures than was the case in Figs. 3 and 4. In Figs. 5 and 6 we must divide the relay-operating figures by the sine of the angle between the local and track currents to give the correct operating figures at the phase displacements shown. It should be noted that in the case of Figs.

3 and 4 the shunt tends to improve the operation of the relay by bringing the local and track currents 9° nearer the "in phase" condition, but in Figs. 5 and 6 the shunt makes the operating conditions of the relay worse, as the phase angle between the track and local currents is now reduced by 8° on a relay on which the best operating condition is 90° out of phase.

The conditions shown in Figs. 3, 4, 5, and 6, are excellent so long as one of the track rails can be spared for signalling purposes only, but when both rails are required for the propulsion return current the addition of the impedance bonds necessary to carry this current alters the vector diagram as shown in Figs. 7 and 8. In the case of Fig. 7, a track circuit in which impedance bonds of low power factor are connected across each end of the track circuit is shown, the relay is of the "in phase" type and it will be seen that the comparatively low impedance and low power factor of the two bonds reduce the shunt at the transformer end of the track to 0·134 ohm, as shown in Fig. 8. The phase angle

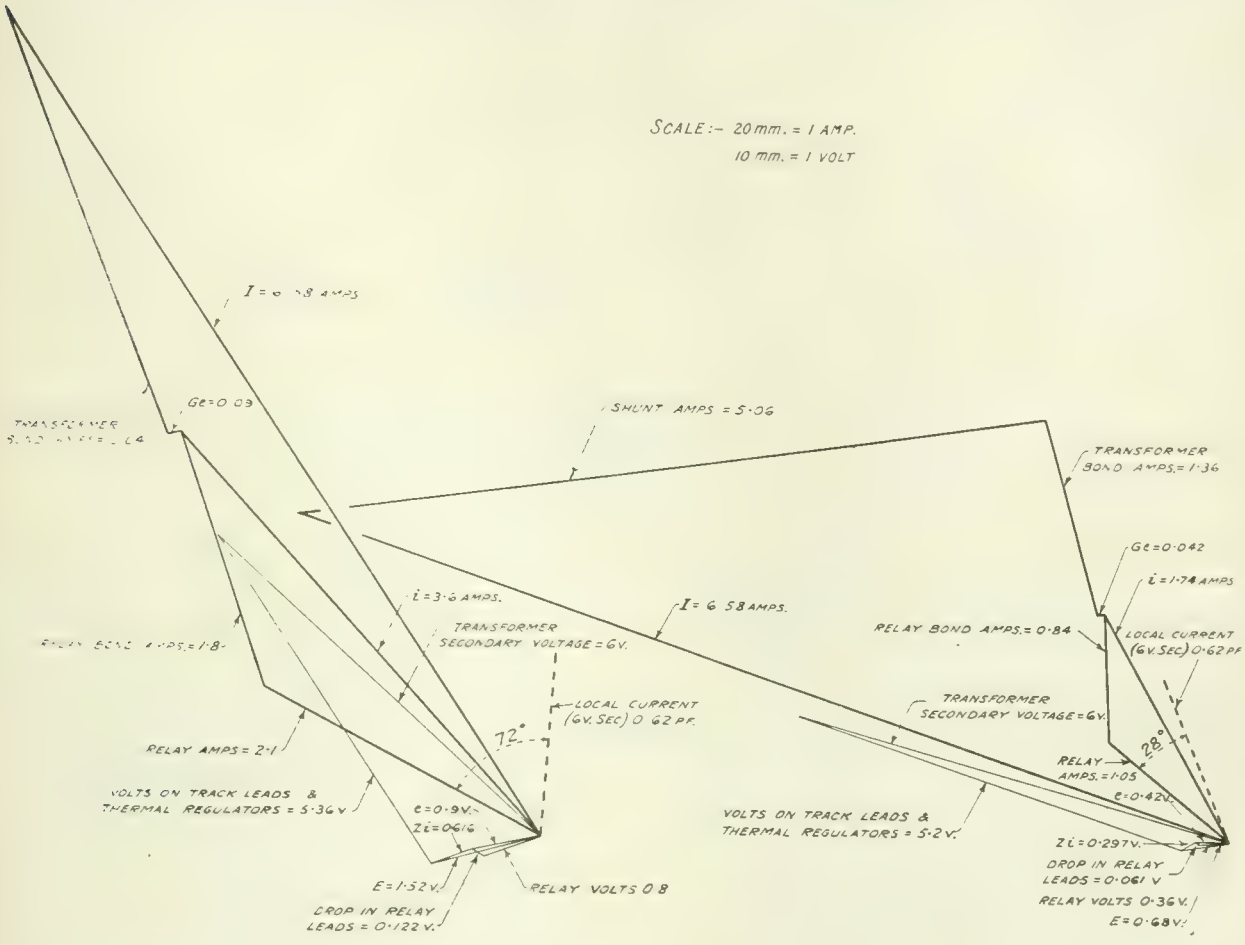

FIG. 7.—Double rail track with impedance bonds, resistance in feed, and galvanometer relay. Supply, 33⅓ cycles. Track circuit, 1,000 ft. long. (Track clear.)

Galvo Relay. Local 50 v. 0·322 amp. 0·62 P.F.
Track 0·8 v. 2·1 amp. 0·65 P.F.
Impedance Bond. Air gap 0·01 in. Imp. 0·5 at 0·128 P.F.
Rail Impedance, Z, = 0·1711 ohm per 1,000 ft. at 0·399 P.F.
Track Conductance, G. Ballast Res. 10 ohms per 1,000 ft. Then G = 0·1.
Relay to be 15 ft. from track. 30 ft. of 7/22.

$$\text{Res. of leads } \frac{1{\cdot}93}{1{,}000} \times 30 = 0{\cdot}058 \text{ ohm.}$$

Drop in relay leads = 0·058 × 2·1 = 0·122 v.
Volts on track, relay end, e = 0·8 + 0·122 = 0·9 v.

$$\text{Amps., Bond, relay end, } = \frac{0{\cdot}9}{0{\cdot}5} = 1{\cdot}8.$$

Amps., relay end, i = 2·1 − 1·8 = 3·6.
Total Volts, E = 0·8 + 0·122 + 0·616 = 1·52 v.
Total Amps., I = 2·1 + 1·8 − 0·09 − 3·04 = 6·58.

$$\text{Amps., Bond, transf. end, } \frac{1{\cdot}52}{0{\cdot}5} = 3{\cdot}04.$$

Track leads 15 ft. long (30 ft. of 7/22). Res. 0·058 ohm.
Drop in track leads, 0·058 × 6·58 = 0·38 v.

FIG. 8.—Train shunt at transformer end of track.

Relay Release figures, 0·36 v. 1·05 amp. 0·73 P.F.
Rail Impedance and Track Conductance as above.
Drop in relay leads 0·058 × 1·05 = 0·061 v.
Volts on track, relay end, e = 0·36 + 0·061 = 0·42 v.

$$\text{Amps., Bond, relay end, } \frac{0{\cdot}42}{0{\cdot}5} = 0{\cdot}84.$$

Amps., relay end, i, $1{\cdot}05 + \overline{0{\cdot}84} - \overline{1{\cdot}7}$.
Total Volts, E, 0·36 + 0·061 − 0·297 = 0·68 v.

$$\text{Amps., Bond, transf. end, } \frac{0{\cdot}68}{0{\cdot}5} = 1{\cdot}36.$$

Total Amps., I = 6·58.
Shunt Amps. = 5·06.

$$\therefore \text{ Resistance of shunt } \frac{0{\cdot}68}{5{\cdot}06} = 0{\cdot}134 \text{ ohm.}$$

between the track and local currents is also large when the track is clear, and small when the track is shunted, being 72° in the first case and 28° in the second. This may be described as a distinctly bad case, as the relay condition (i.e. the phase angle between the local and track currents) is improved when the track is shunted, 19° out of quadrature with the track clear, and 17° out of quadrature with the track shunted.

An interesting point in these two diagrams is that with a certain shunt resistance, which is slightly higher than that necessary to drop the relay, the track and local currents will be exactly in quadrature and the

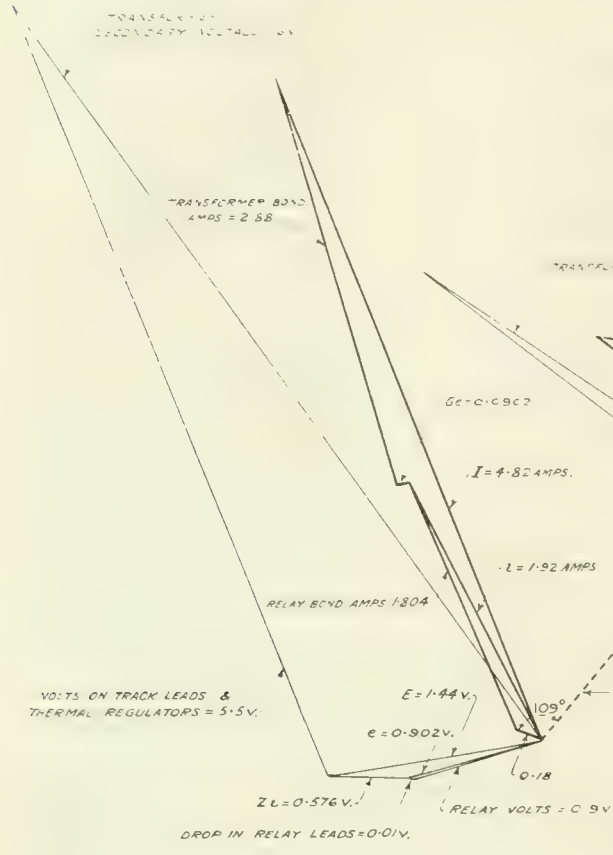

FIG. 9.—Double rail track with impedance bonds, resistance in feed, and two-element vane relay. 50 cycles. Track circuit, 1,000 ft. long. (Track clear.)

Two element Vane Relay, Local 100 v. 0·44 amp. 0·25 P.F.
Track 0·9 v. 0·18 amp. 0·8 P.F.
Impedance Bonds, Air-gap 0·01 in., Imp. 0·5 at 0·128 P.F.
Rail Impedance, Z, 0·3 ohm per 1,000 ft. at 0·5 P.F.
Track Conductance. Ballast Res. 10 ohms per 1,000 ft. Then G = 0·1.
Relay to be 15 ft. from track. 30 ft. of 7/22.

Reserve of leads $\frac{1·93}{1,000} \times 30 = 0·058$ ohm.

Drop in relay leads = 0·058 × 0·18 = 0·01 v.

Volts on track relay end, $e = 0·9 + 0·01 = 0·902$ v.

Amps., Bond, relay end, $= \frac{0·902}{0·5} = 1·804$

Amps., relay end, $i = \frac{0·18}{1·804} = 1·92$.

Total Volts, E = 0·9 + 0·01 + 0·576 = 1·41 v.

Amps., Bond, transf. end, $= \frac{1·44}{0·5} = 2·88$.

Total Amps. = 0·18 + 1·804 + 0·902 = 2·86 = 4·82.
Track leads, 30 ft. of 7/22
Drop in track leads = 0·058 × 4·82 = 0·27 v.

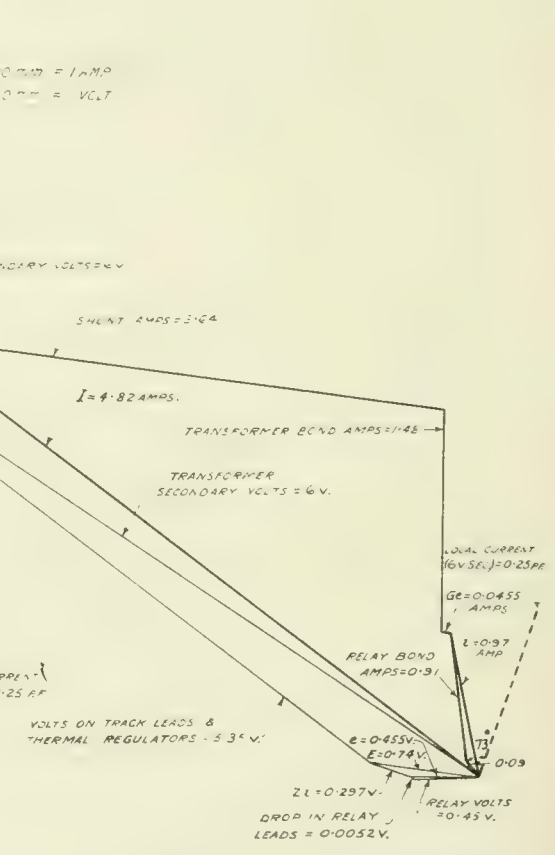
SCALE – 20 mm = 1 AMP
20 mm = 1 VOLT
SHUNT AMPS = 3·64
I=4·82 AMPS.
TRANSFORMER BOND AMPS = 1·48
TRANSFORMER SECONDARY VOLTS = 6 V.
LOCAL CURRENT (6V SEC.) = 0·25 PF
Ge=0·0455 AMPS
i=0·97 AMP
RELAY BOND AMPS=0·91
VOLTS ON TRACK LEADS & THERMAL REGULATORS = 5·5 V.
e=0·455 V.
E=0·74 V.
73°
0·09
Zt=0·297 V.
RELAY VOLTS =0·45 V.
DROP IN RELAY LEADS = 0·0052 V.

FIG. 10.—Train shunt at transformer end of track.

Relay release figures, 0·45 v. 0·09 amp. 0·8 P.F
Drop in relay leads, 0·058 × 0·09 = 0·0052 v.
Volts on track, relay end, $e = 0·45 \times 0·0052 = 0·455$ v.
Amps., Bond, relay end, $\frac{0·455}{0·5} = 0·91$.
Amps., relay end, $i = 0·09 - 0·91 = 0·97$.
Total Volts, E = 0·45 + 0·0052 + 0·297 = 0·74 v.
Amps., Bond, transf. end, $\frac{0·74}{0·5} = 1·48$ v.
Total Amps., I = 4·82.
Shunt Amps. = 3·64.
∴ Resistance of shunt $\frac{0·74}{3·64} = 0·201$ ohm.

thus necessitating a lower shunt resistance to drop the relay.

The quadrature relay is obviously more suitable for use with this type of impedance bond, and Figs. 9 and 10 show the track-circuit conditions with such a relay. In the case of Fig. 9 the relay is operating relay will be operating under its best conditions. The reduction in the total current to the track when using the two-element vane relay is particularly noticeable. The track current, however, is still large, and transformers and track leads and resistance would be large in proportion. The large currents passed by the two

impedance bonds account for the high total current, and if we can increase the impedance of these bonds so as to reduce these current vectors, we shall also be able to reduce the size of our track transformer, resistance and leads to correspond. The reduction in track current shown in Figs. 11 and 12 is due to the use of resonated impedance bonds, details of which are given elsewhere in this paper. In Fig. 11 an "in phase" relay is shown operating on a track circuit with a phase displacement of 24° between the track

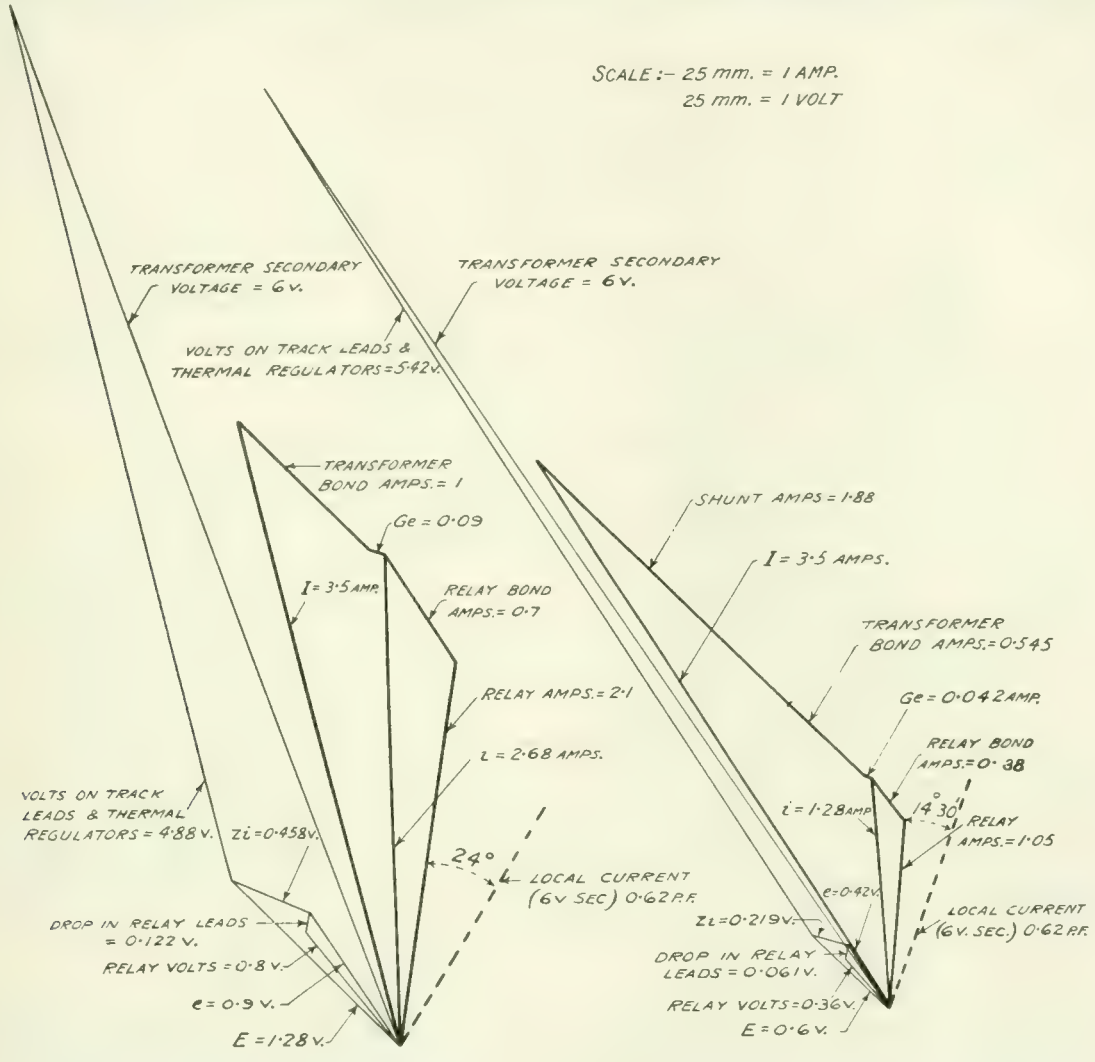
SCALE :– 25 mm. = 1 AMP.
25 mm. = 1 VOLT
TRANSFORMER SECONDARY VOLTAGE = 6 V.
TRANSFORMER SECONDARY VOLTAGE = 6 V.
VOLTS ON TRACK LEADS & THERMAL REGULATORS = 5·42 V.
TRANSFORMER BOND AMPS. = 1
Ge = 0·09
I = 3·5 AMP.
RELAY BOND AMPS. = 0·7
RELAY AMPS. = 2·1
i = 2·68 AMPS.
VOLTS ON TRACK LEADS & THERMAL REGULATORS = 4·88 V.
Zi = 0·458 V.
24°
LOCAL CURRENT (6 V SEC) 0·62 P.F.
DROP IN RELAY LEADS = 0·122 V.
RELAY VOLTS = 0·8 V.
e = 0·9 V.
E = 1·28 V.
SHUNT AMPS = 1·88
I = 3·5 AMPS.
TRANSFORMER BOND AMPS. = 0·545
Ge = 0·042 AMP.
RELAY BOND AMPS. = 0·38
i = 1·28 AMP.
14° 30'
RELAY AMPS. = 1·05
e = 0·42 V.
Zi = 0·219 V.
LOCAL CURRENT (6 V. SEC.) 0·62 P.F.
DROP IN RELAY LEADS = 0·061 V.
RELAY VOLTS = 0·36 V.
E = 0·6 V.

FIG. 11.—Double rail track with resonated impedance bonds, resistance in feed, and galvanometer relay. Supply, $33\frac{1}{3}$ cycles. Track circuit, 1,000 ft. long. (Track clear.)

Galvo. Relay, Local 50 v. 0·322 amp. 0·62 P.F.
Track 0·8 v. 2·1 amps. 0·68 P.F.
Resonated Impedance Bonds. Air-gap 0·025 in. Imp. 1·28 ohms at Unity P.F.
Rail Impedance, Z. 0·1711 ohm per 100 ft. at 0·399 P.F.
Track Conductance, G. Ballast Res. 10 ohms per 1,000 ft. Then G = 0·1.
Relay to be 15 ft. from track. 30 ft. of 7/22.

Resistance of leads $\frac{1·93}{1,000} \times 30 = 0·058$ ohm.

Drop in relay leads = 0·058 + 2·1 = 0·122 v.
Volts on track, relay end, $e = \sqrt{0·8^2 + 0·122^2} = 0·9$ v.

Amps., Bond, relay end, $= \frac{0·9}{1·28} = 0·7$.

Amps., relay end, $i = \sqrt{2·1^2 - 0·7^2} = 2·68$.
Total Volts, $E = \sqrt{0·8^2 + 0·122^2} = 1·28$ v.

Amps. Bond, transformer end, $\frac{1·28}{1·28} = 1$ amp.

Total Amps., I = 2·1 + 0·7 + 0·09 + 1 = 3·5.
Track leads 15 ft. long. 30 ft. of 7/22.
Drop in track leads = 0·058 × 3·5 = 0·203 v.

FIG. 12.—Train shunt at transformer end of track.

Relay Release figures, 0·36 v. 1·05 amp. 0·73 P.F.
Rail Impedance and Track Conductance as above.
Drop in relay leads, 0·058 × 1·05 = 0·061 v.
Volts on track relay end, e = 0·36 + 0·061 = 0·42 v.

Amps. Bond, relay end, $= \frac{0·42}{1·7} = 0·38$.

Amps., relay end, $i = \sqrt{1·05^2 + 0·38^2} = 1·28$.
Total Volts, $E = \sqrt{0·36^2 + 0·061^2} = 0·6$ v.

Amps. Bond, transf. end, $= \frac{0·6}{1·1} = 0·545$.

Total Amps., I = 3·5.
Shunt Amps. = 1·88.

∴ Resistance of shunt $= \frac{0·6}{1·88} = 0·319$ ohm.

and local currents with the track clear, and releasing with a shunt resistance of 0·319 ohm and a phase displacement of 14° 30′ with the track shunted at the transformer end of the track.

to this improvement we must also count the improved phase relationship of the track and local currents shown in Figs. 11 and 12, and particularly the small relative change in this phase relationship which now takes

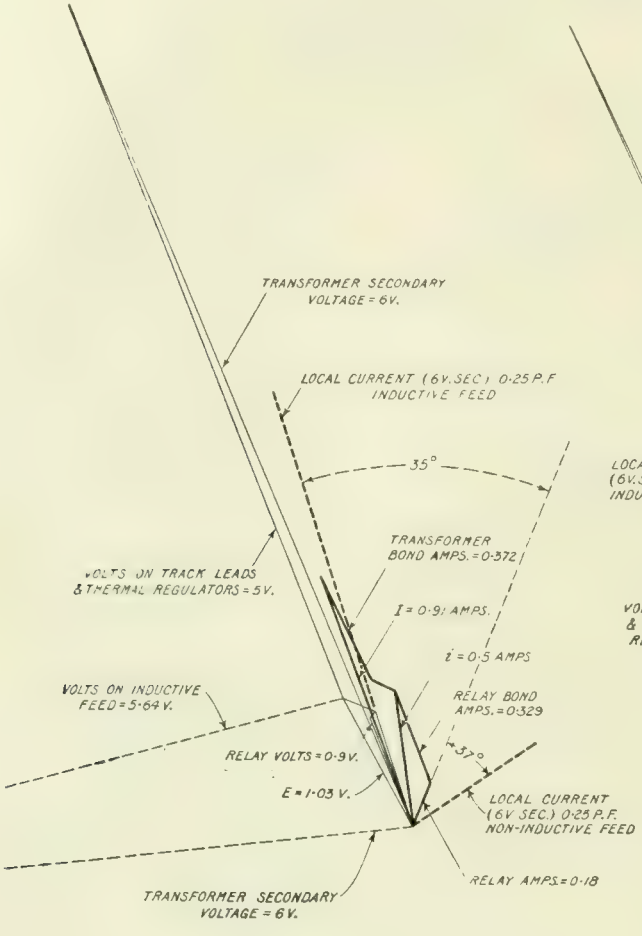
TRANSFORMER SECONDARY VOLTAGE = 6V.
LOCAL CURRENT (6V.SEC.) 0·25 P.F. INDUCTIVE FEED
35°
TRANSFORMER BOND AMPS. = 0·372
VOLTS ON TRACK LEADS & THERMAL REGULATORS = 5V.
I = 0·91 AMPS.
i = 0·5 AMPS
VOLTS ON INDUCTIVE FEED = 5·64 V.
RELAY BOND AMPS. = 0·329
37°
RELAY VOLTS = 0·9V.
E = 1·03 V.
LOCAL CURRENT (6V SEC.) 0·25 P.F. NON-INDUCTIVE FEED
RELAY AMPS. = 0·18
TRANSFORMER SECONDARY VOLTAGE = 6V.

FIG. 13.—Double rail track with resonated impedance bonds, resistance in feed, and two-element vane relay. Supply, 50 cycles. Track circuit, 1,000 feet long. (Track clear.)

Two-element Vane Relay, Local 100 v. 0·44 amp. 0·25 P.F.
Track 0·9 v. 0·18 amp. 0·8 P.F.
Impedance Bonds, 0·06 in. air-gap. Imp. 2·74 at Unity P.F.
Rail Impedance, Z = 0·3 per 1,000 ft. at 0·5 P.F.
Track Conductance, G. Ballast Res. 10 ohms. ∴ G = 0·1.
Relay to be 15 ft. from track. 30 ft. of 7/22.

$$\text{Res. of leads} = \frac{1\cdot93}{1,000} \times 30 = 0\cdot058 \text{ ohm.}$$

Drop in relay leads = $0\cdot058 \times 0\cdot18 = 0\cdot01$ v.
Volts on track, relay end, $e = 0\cdot9 + 0\cdot01 = 0\cdot902$ v.

$$\text{Amps., Bond, relay end,} = \frac{0\cdot902}{2\cdot74} = 0\cdot329.$$

Amps., relay end, $i = 0\cdot18 + 0\cdot329 = 0\cdot5$.
Total Volts, $E = 0\cdot9 + 0\cdot01 + 0\cdot15 = 1\cdot03$ v.

$$\text{Amps., Bond, transformer end,} \frac{1\cdot03}{2\cdot74} = 0\cdot372.$$

Total Amps., $I = 0\cdot18 + 0\cdot329 + 0\cdot0902 + 0\cdot372 = 0\cdot91$.
Track leads 15 ft. long. 30 ft. of 7/22.
Drop in track leads, $0\cdot058 \times 0\cdot91 = 0\cdot052$ v.

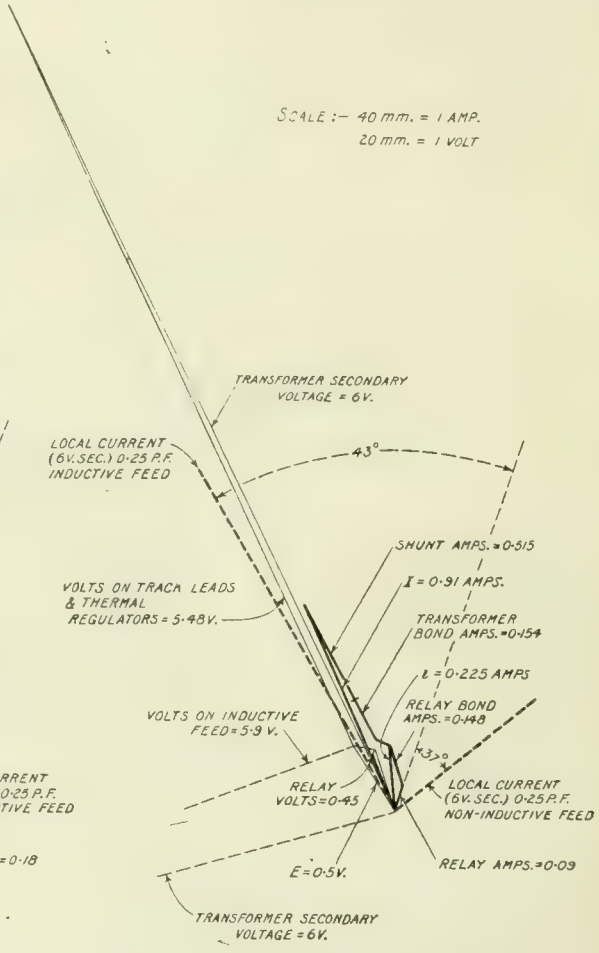
SCALE :– 40 mm. = 1 AMP.
20 mm. = 1 VOLT
TRANSFORMER SECONDARY VOLTAGE = 6V.
LOCAL CURRENT (6V.SEC.) 0·25 P.F. INDUCTIVE FEED
43°
SHUNT AMPS. = 0·515
I = 0·91 AMPS.
VOLTS ON TRACK LEADS & THERMAL REGULATORS = 5·48V.
TRANSFORMER BOND AMPS. = 0·154
i = 0·225 AMPS
RELAY BOND AMPS. = 0·148
VOLTS ON INDUCTIVE FEED = 5·9 V.
43°
RELAY VOLTS = 0·45
LOCAL CURRENT (6V.SEC.) 0·25 P.F. NON-INDUCTIVE FEED
E = 0·5V.
RELAY AMPS. = 0·09
TRANSFORMER SECONDARY VOLTAGE = 6V.

FIG. 14.—Train shunt at transformer end of track.

Relay Release figures, 0·45 v. 0·09 amp. 0·8 P.F.
Drop in relay leads, $0\cdot058 \times 0\cdot09 = 0\cdot0052$ v.
Volts on track, relay end, $e = 0\cdot45 + 0\cdot0052 = 0\cdot455$ v.

$$\text{Amps., Bond, relay end,} \frac{0\cdot455}{3\cdot06} = 0\cdot148.$$

Amps., relay end, $i = 0\cdot09 + 0\cdot148 = 0\cdot225$.
Total Volts, E, $0\cdot45 + 0\cdot0052 + 0\cdot0675 = 0\cdot5$ v.

$$\text{Amps. Bond, transf. end} = \frac{0\cdot5}{3\cdot25} = 0\cdot154.$$

Total Amps., I = 0·91.
Shunt Amps. = 0·515.

$$\therefore \text{ Resistance of shunt} = \frac{0\cdot5}{0\cdot515} = 0\cdot97 \text{ ohm.}$$

The reduction in the total track current obtained by using the resonated bonds has improved the shunt values shown in Figs. 7 and 8 by 230 per cent on the same track circuit and with the same relay. In addition

place when the track is shunted. In Figs. 7 and 8 the phase angle improved from 72° to 28° with the track shunted, a change of 50°, whereas in Figs. 11 and 12 the improvement is only 9° 30′.

Neither of these cases represents the best results obtainable, as in Figs. 11 and 12 it is still possible to improve the relay-operating conditions by adjusting the resonated impedance bonds to have a leading power factor and so compensate for the 24° difference between the track and local currents. If a quadrature relay is used with the resonated type of bond and resistance in the track feed as shown in Figs. 13 and 14, the relay will be operating with a phase displacement of 36° between the track and local currents with the track clear, and 38° with the track shunted. This is unsatisfactory, and cannot be corrected with either the induct-

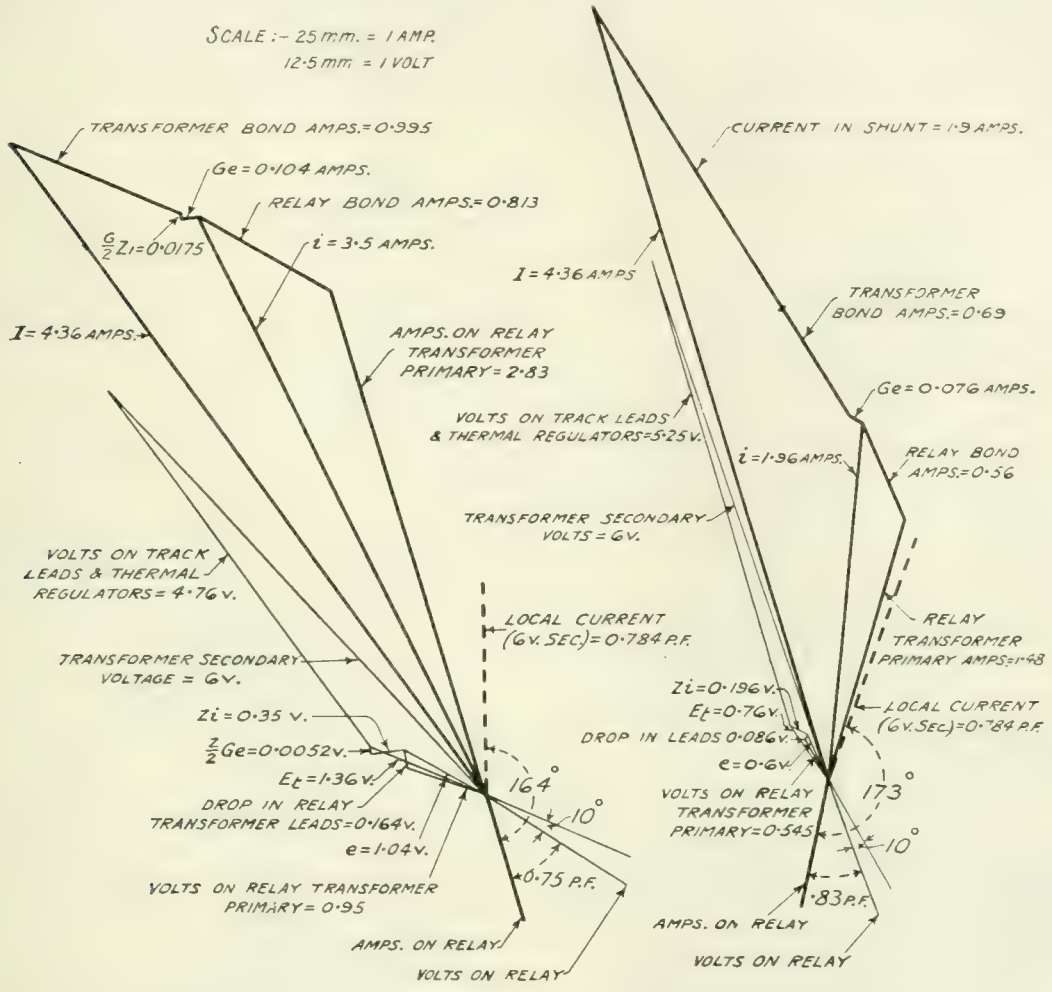

FIG. 15.—Double rail track circuit with resonated impedance bonds, resistance in feed, relay transformer, and galvanometer relay. Supply, 25 cycles. Track circuit, 1,000 feet long. (Track clear.)

Galvanometer relay, Local 50 volt, 0·327 amp. 0·784 P.F.
Track 12 volt, 0·2 amp. 0·75 P.F.

Relay Transformer (ratio 1·5 19 v.).

Track $= \frac{1·5 \cdot 12}{19} = 0·95$ volt. $0·2 + \frac{864}{68} + \frac{100}{90} = 2·83$ amps. at 0·6 P.F.

Resonated Impedance Bond, Air-gap 0·025 in.
Rail Impedance, Z = 0·1 ohm per 1,000 ft. at 0·43 P.F.
Track Conductance, G = 0·1 (Ballast resistance = 10 ohms).
Relay to be 15 ft. from track. 30 ft. of 7/22 S.W.G.

Resistance of leads $= \frac{1·93}{1,000} \times 30 = 0·058$ ohm.

Drop in relay leads = $0·058 \times 2·83 = 0·164$ volt.

Volts on track, relay end, $e = 0·95 + 0·164 = 1·04$ volts.

Amps., Bond, relay end, $\frac{1·04}{1·28} = 0·813$ amp.

Amps., relay end, $i = 2·83 \times 0·813 = 3·5$ amps.

Total Volts, $E = 0·95 + 0·164 + 0·35 + 0·0052 = 1·36$ volts.

Amps., Transformer bond, $= \frac{1·36}{1·4} = 0·995$ amp.

Track leads, 30 ft. 7/22 S.W.G. Drop in leads $0·058 \times 4·36 = 0·25$ volt.

Total Amps., $I = 3·5 + 0·104 + 0·0175 + 0·995 = 4·36$ amps.

FIG. 16.—Train shunt at transformer end of track.

Relay release figures, Track, 6·9 volts. 0·105 amp. 0·83 P.F.

Relay Transformer. Track $\frac{1·5 \times 6·9}{19} = 0·545$ volt. Amps. = 1·48 P.F. 0·7 v.

Drop in relay leads $0·058 \times 1·48 = 0·086$.

Volts on track, relay end, $e = 0·545 + 0·086 = 0·6$ v.

Amps., Bond, relay end, $= \frac{0·6}{1·07} = 0·56$ amp.

Amps., relay end, $i = 1·48 + 0·56 = 1·96$.

Total Volts, $E = 0·545 + 0·086 - 0·196 = 0·76$ v.

Amps., Bond, Transformer end, $= \frac{0·76}{1·1} = 0·69$ amp.

Shunt Amps. = 1·9. Total Amps., I = 4·36 amps.

∴ Resistance of shunt $= \frac{0·76}{1·9} = 0·4$ ohm.

ance or the resistance method of feeding; as, in one case, the track current lags 37° from the local current, and in the other case it leads by 36°, neither case giving the desired quadrature results.

The shunt value obtained with the quadrature relay in Fig. 14 is higher than that obtained in Fig. 11, because the frequency of the supply enabled a higher impedance to be obtained on the resonated impedance bond, and also because the volt-amperes required from the track to operate the quadrature relay were less than those required to operate the "in phase" relay.

It is frequently desirable to place the track relay at some distance from the end of the track circuit, and in order to do this economically with regard to cable, a relay transformer is inserted, the track voltage being stepped up for transmission to the relay. One result of using the relay transformer is to introduce a further complication in the vector diagram, as the displacement between the primary and secondary voltage vectors cannot be taken as exactly 180° in certain transformers of the smaller size (approximately 5 volt-amperes) used for this work. Phase displacement between primary and secondary voltages in this type sometimes reaches as much as 10° from the 180°. In addition to this, there is the displacement of the current vector which is not the same in primary and secondary windings. The relay constitutes an inductive load on the secondary of the relay transformer, and the power factor of the

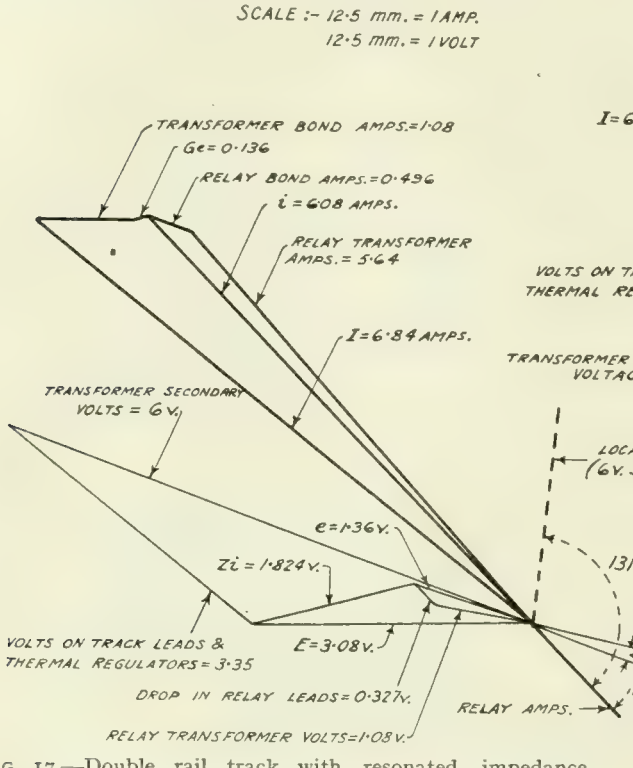

FIG. 17.—Double rail track with resonated impedance bonds, resistance in feed, relay transformer and two-element vane relay. Supply, 60 cycles. Track circuit, 1,000 feet long. (Track clear.)

Two-element Vane Relay, Local 100 v. 0·44 amp. 0·25 P.F.
Track 15 v. 0·4 amp. 0·9 P.F.
Relay Transformer. (Ratio 1·5/19 v.)
Track, $\frac{1\cdot5}{19} \times 15 = 1\cdot08$ v.

$0\cdot4 \times$ Ratio of turns $\times \frac{100}{90} = 5\cdot64$ amps. 0·8 P.F.

Resonated Impedance Bonds. 0·06 in. air-gap.
Rail Impedance, Z = 0·3 ohm. per 1,000 ft. at 0·5 P.F.
Track Conductance. Ballast Res. 10 ohms. Then G = 0·1.
Relay to be 15 ft. from track. 30 ft. of 7.22.

Res. of leads $\frac{1\cdot93}{1{,}000} \times 30 = 0\cdot058$ ohm.

Drop in relay leads = $0\cdot058 \times 5\cdot64 = 0\cdot327$ v.
Volts on track, relay end, $e = 1\cdot08 + 0\cdot327 = 1\cdot36$ v.

Amps. Bond, relay end, $\frac{1\cdot36}{2\cdot74} = 0\cdot496$.

Amps., relay end, $i = 5\cdot64 + 0\cdot496 = 6\cdot08$.
Total Volts, $E = 1\cdot08 + 0\cdot327 + 1\cdot824 = 3\cdot08$ v.

Amps., Bond, transf. end, $= \frac{3\cdot08}{2\cdot86} = 1\cdot08$.
Track leads, 30 ft. of 7.22. Drop in leads $0\cdot058 \times 6\cdot84 = 0\cdot396$ v.
Total Amps., $I = 5\cdot64 + 0\cdot496 + 0\cdot136 + 1\cdot08 = 6\cdot84$.

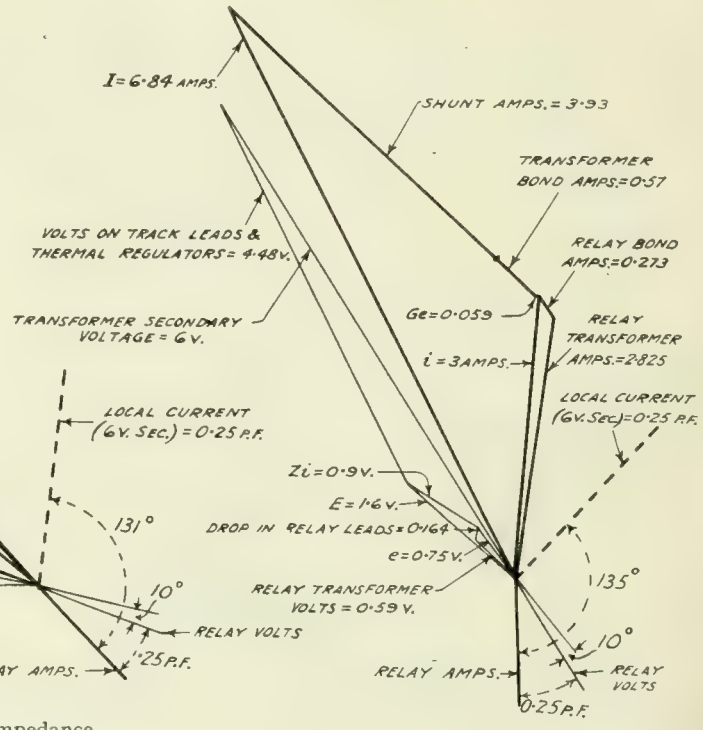

FIG. 18.—Train shunt at transformer end of track.

Relay Release figures, Track 7·5 v. 0·2 amp. 0·906 P.F.
Relay transformer. Track $\frac{1\cdot5 \times 7\cdot5}{19} = 0\cdot59$ v. 2·825 amp. 0·6 P.F.
Rail Impedance and Track Conductance as above.
Drop in relay leads, $0\cdot058 \times 2\cdot825 = 0\cdot164$ v.
Volts on track, relay end, $e = 0\cdot59 + 0\cdot164 = 0\cdot75$ v.

Amps., Bond, relay end $= \frac{0\cdot75}{2\cdot78} = 0\cdot273$.

Amps., relay end, $i = 2\cdot825 + 0\cdot273 = 3$.
Total Volts, $E = 0\cdot59 + 0\cdot164 + 0\cdot9 = 1\cdot6$ v.

Amps., Bond, transf. end, $= \frac{1\cdot6}{2\cdot8} = 0\cdot57$.

Total Amps., $I = 6\cdot84$.
Shunt Amps. $= 3\cdot93$.

∴ Resistance of Shunt $= \frac{1\cdot6}{3\cdot93} = 0\cdot407$ ohm.

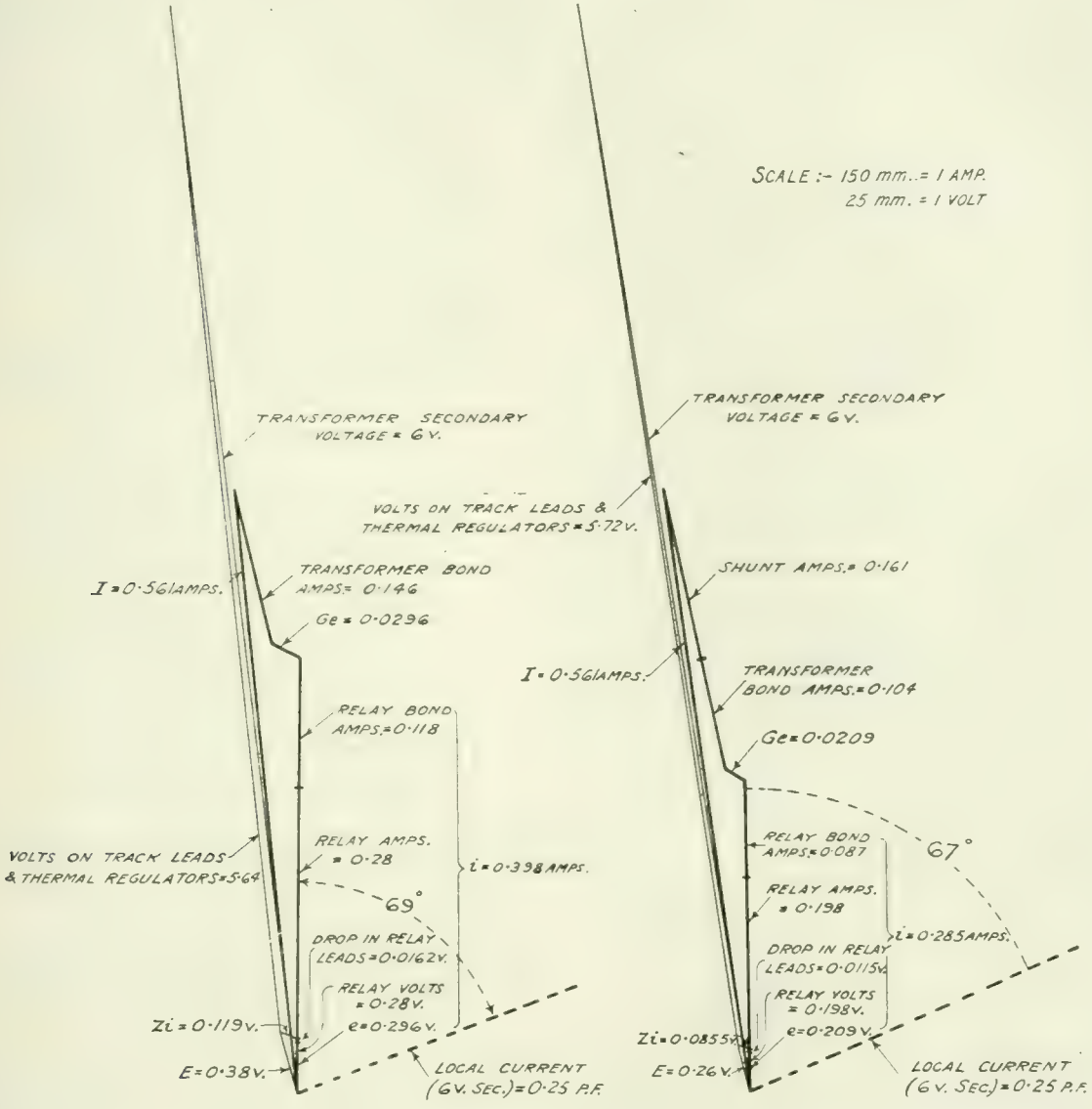
TRANSFORMER SECONDARY VOLTAGE = 6 V.
I = 0·561 AMPS.
TRANSFORMER BOND AMPS = 0·146
Ge = 0·0296
RELAY BOND AMPS = 0·118
VOLTS ON TRACK LEADS & THERMAL REGULATORS = 5·64
RELAY AMPS. = 0·28
i = 0·398 AMPS.
69°
DROP IN RELAY LEADS = 0·0162 V.
RELAY VOLTS = 0·28 V.
Zi = 0·119 V.
e = 0·296 V.
E = 0·38 V.
LOCAL CURRENT (6 V. SEC.) = 0·25 P.F.
SCALE :- 150 mm. = 1 AMP.
25 mm. = 1 VOLT
TRANSFORMER SECONDARY VOLTAGE = 6 V.
VOLTS ON TRACK LEADS & THERMAL REGULATORS = 5·72 V.
SHUNT AMPS. = 0·161
I = 0·561 AMPS.
TRANSFORMER BOND AMPS. = 0·104
Ge = 0·0209
RELAY BOND AMPS. = 0·087
67°
RELAY AMPS. = 0·198
i = 0·285 AMPS.
DROP IN RELAY LEADS = 0·0115 V.
RELAY VOLTS = 0·198 V.
Zi = 0·0855 V.
e = 0·209 V.
E = 0·26 V.
LOCAL CURRENT (6 V. SEC.) = 0·25 P.F.

FIG. 19.—Double rail track with resonated impedance bonds, two-element vane relay and condenser in track winding. Supply, 60 cycles. Track circuit, 1,000 feet long. (Track clear.)

Two-element Vane Relay, Local 100 v. 0·44 amp. 0·25 P.F.
Track 0·29 v. 0·28 amp. unity P.F.
Resonated Impedance Bonds. 0·06 in. air gap. Unity P.F.
Rail Impedance, Z. 0·3 ohm per 1,000 ft. at 0·5 P.F.
Track Conductance, G. Ballast Res. 10 ohms per 1,000 ft. $\therefore$ G = 0·1.
Relay to be 15 ft. from track. 30 ft. of 7/22.

Resistance of leads = $\frac{1·93}{1,000} \times 30 = 0·058$ ohm.

Drop in relay leads = 0·058 × 0·28 = 0·0162 v.
Volts on track, relay end, $e = \overline{0·28 + 0·0162} = \overline{0·296}$ v.

Amps., Bond, relay end, $= \frac{0·296}{2·5} = 0·118$.

Amps., relay end, $i = \overline{0·28 + 0·118} = 0·398$.
Total Volts, E = 0·28 + 0·0162 + 0·119 = 0·38 v.

Amps., Bond, transformer end, $= \frac{0·38}{2·6} = 0·146$.

Total Amps., $I = 0·28 + \overline{0·118 + 0·0296} + 0·146 = 0·561$
Track leads, 30 ft. of 7/22.
Drop in track leads, 0·058 × 0·561 = 0·0325 v.

FIG. 20.—Train shunt at transformer end of track.

Relay Release figures, 0·198 v. 0·198 amp. unity P.F.
Drop in relay leads 0·058 × 0·198 = 0·0115 v.
Volts on track, relay end, $e = 0·198 + 0·0115 = \overline{0·209}$ v.

Amps., Bond, relay end, $\frac{0·209}{2·4} = 0·087$.

Amps., relay end, $i = 0·198 + 0·087 = 0·285$.
Total Volts, E = 0·198 + 0·0115 + 0·0855 = 0·26.

Amps., Bond transf. end, $\frac{0·26}{2·5} = 0·104$.

Total Amps. I = 0·561.
Shunt Amps., 0·161.

$\therefore$ Resistance of Shunt $= \frac{0·26}{0·161} = 1·62$ ohms.

primary load will of course be lower than that of the secondary owing to the magnetizing current of the transformer, which is supplied from the track.

In Figs. 15 and 16, a double-rail track circuit with resonated impedance bonds is shown. In this case the displacement of the voltage vector on the relay transformer has been taken as 10°. The net result of introducing the relay transformer into the track circuit is to alter the power factor at the relay end of the track from 0·75 on the relay to 0·6 on the track. It will be noted also that the current taken from the track is now high. This is partly due to the losses in the relay transformer, and partly to the fact that it is not as efficient to wind the relay for a high operating voltage as for a low one.

In Figs. 17 and 18 a similar track circuit with a relay transformer and quadrature relay is shown; and the errors introduced by the relay transformer have been allowed for in the same way. The comparison between these two diagrams and Figs. 15 and 16 shows that there is no great advantage in substituting a quadrature relay for the "in phase" relay because the current taken for the primary of the relay transformer is high in each case. The comparison of the two figures shows, in the case of the "in phase" relay, a shunt value of 0·4 ohm, and of the "quadrature" relay 0·407 ohm. It must be remembered, however, that these values have not been corrected for the poor working phase angle at which the relays are shown.

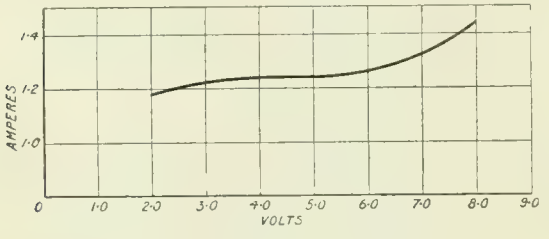

FIG. 21.—Curve of thermal resistance.

The alteration in phase angle that takes place between track "clear" and track "shunted" is small in each case, and therefore the *comparison* in shunt values is permissible. Several methods have been adopted for varying the power factor of the relay in order to enable the best operating conditions to be obtained. One of these, which has been used on the quadrature relay, consists in adding another winding to the iron core on which the track winding of the relay is mounted, and connecting this additional winding to a small capacity. By this means the power factor of the track winding can be brought up to "unity."

Figs. 19 and 20 show a double-rail track circuit with resonated impedance bonds, and a relay in which the power factor of the track winding has been made "unity" by this method. This gives a very good combination for a double-rail track circuit, the normal phase displacement on the relay being 69° and the phase displacement when shunted varying only 2°. It will be noted that the high shunt value of 1·62 ohms is obtained.

Another method of obtaining control of the phase angle on the relay is to feed the track circuit through a condenser of variable capacity, or, alternatively, to use a capacity and inductance in series, the two being so adjusted in relation to one another that the current supply to the track may be given an angle of "lag" or "lead" as desired. The method of doing this is shown in Fig. 27. The supply feeds the primary of a "step-down" transformer through a condenser, the secondary of the transformer being connected direct to the track rails with or without intermediate means of regulation. Adjustment may be made by suitably varying the number of turns of the primary winding, capacity being maintained constant.

Damage from pressure-rises due to any cause is protected against by the use of safety spark-gaps across the condenser terminals. By adjusting the

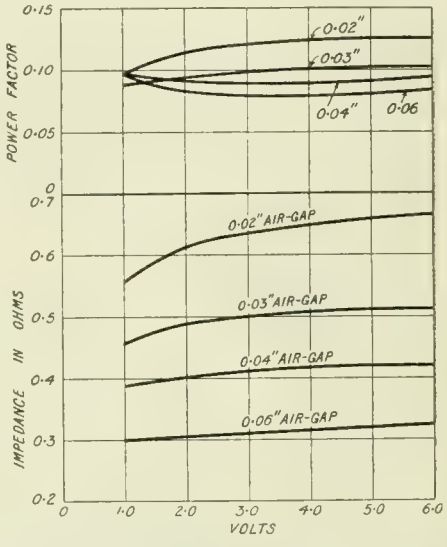

FIG. 22.—Curves showing impedance and power factor of resonated bond with various air-gaps. Capacity of bond 750 D.C. amperes per rail.

number of primary turns in relation to the capacity, the voltage across the condenser can be maintained at a point slightly above the pressure of the mains while the track is "clear." When the track is "shunted," however, the short-circuit of the secondary winding of the transformer so reduces the inductance of the transformer that the pressure of the mains only is placed across the condenser terminals. This results in a decrease of the current passed by the condenser and, of course, a corresponding decrease in the current output to the track on the secondary side. This is of great value in the track circuit as it enables a higher shunt value to be obtained.

Not only does a decrease in current take place, but a change in the phase angle of the current also. This changing of the phase angle can be utilized to improve still further the shunt value, by so arranging the track circuit that with the track "clear" the relay is operating at its maximum efficiency, and that when the track is "short-circuited" the phase angle changes in such a way as to make the relay-operating conditions less

efficient. This method of feeding is most suitable for single-rail track circuits fitted with quadrature relays. In this case the capacity and inductance in series are so adjusted that their power factor is " unity,"

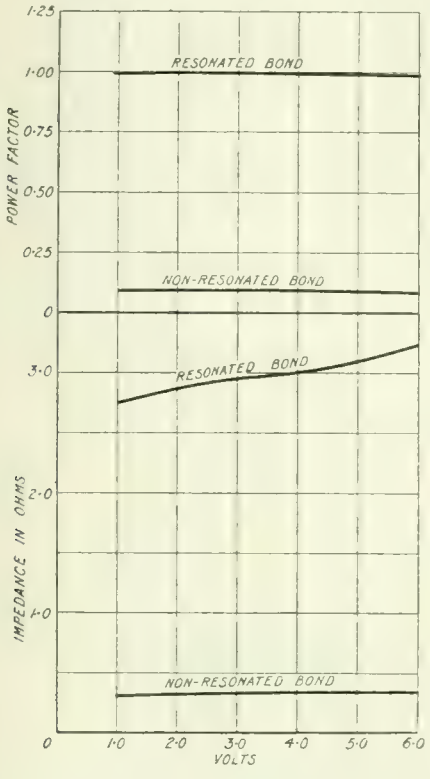

FIG. 23.—Curves showing comparison of impedance and power factor of resonated and non-resonated bonds. 750 D.C. amperes per rail. 0·06 in. air-gap. 50 cycles

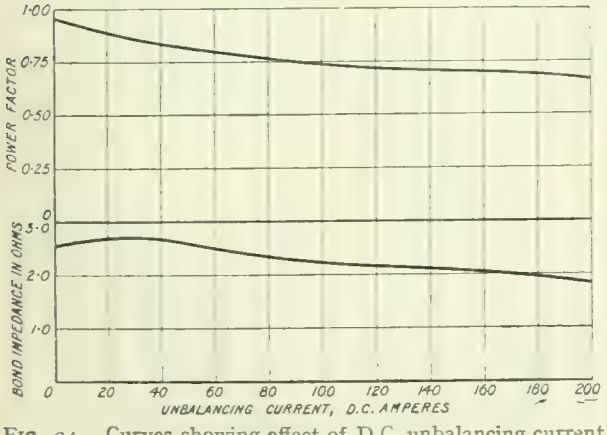

FIG. 24.—Curves showing effect of D.C. unbalancing current on resonated bond, impedance and power factor at 50 cycles. Capacity of bond 750 D.C. amperes per rail. Air-gap = 0·06 in. A.C. track voltage = 2 volts.

the quadrature relay itself being designed so that its two windings have widely different power factors.

When the track is " clear," the capacity and inductance supply current which gives a 90° phase displacement on the relay; and when the track is short-circuited and the inductance of the feed transformer thereby reduced, the condenser supplies a leading current which brings the phase angle of the two currents on the relay to a phase displacement of less than 90°.

Another method of altering the power factor of the

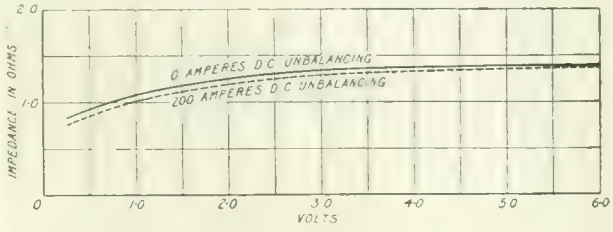

FIG. 25.—Curves showing impedance with zero and with 200 amperes unbalanced direct current. 25 cycles. Resonated bond.

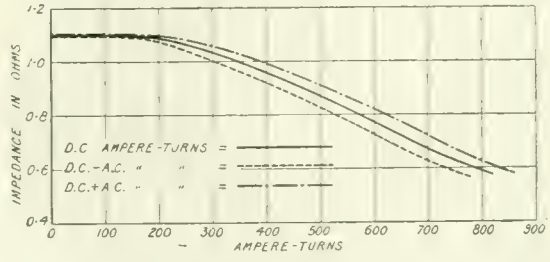

FIG. 26.—Variation in A.C. relay impedance with superimposed direct current.

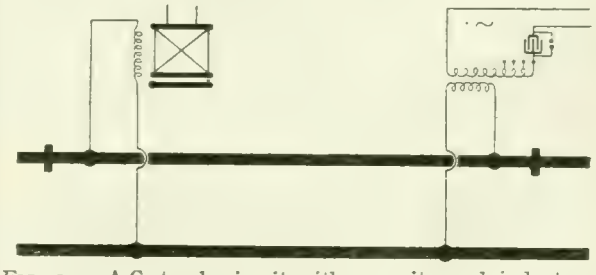

FIG. 27.—A.C. track circuit with capacity and inductance in feed circuit.

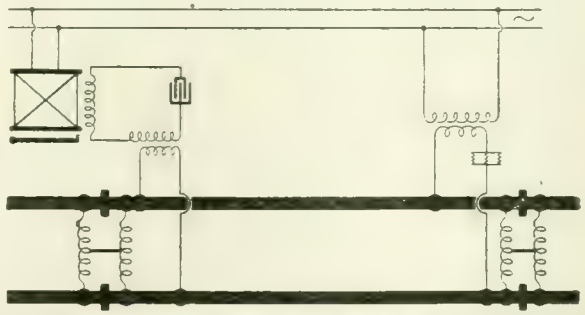

FIG. 28.—A.C. track circuit with relay transformer and condenser in series with relay.

relay track element to suit all the conditions consists in introducing a capacity between the high-voltage side of a relay transformer and the relay track element, as shown in Fig. 28. This, however, does not give to the track when " shunted " the falling current output

which can be obtained by feeding the track circuit through the combination of inductance and capacity.

Referring to Fig. 28, where a small capacity is introduced between the secondary of the relay transformer and the relay track winding. This method gives similar results to that of adding a condenser winding and condenser to the relay, but has the advantage that the relay need not be altered. This is an advantage, as a standard design of relay can be used with or without the relay transformer, and with either the resonated or the non-resonated bond. The results obtained with this method are given here for a typical case of a single-rail track circuit approximately 1,000 feet long, the ballast resistance being 5 ohms.

Readings were taken with a phase-meter, one winding of the instrument being connected across the primary side of the feed transformer, and the other winding being connected across the following points: (*a*) The non-inductive feed resistance. (*b*) The track rails at the transformer end. (*c*) The track rails at the relay end. (*d*) The primary of the relay transformer.

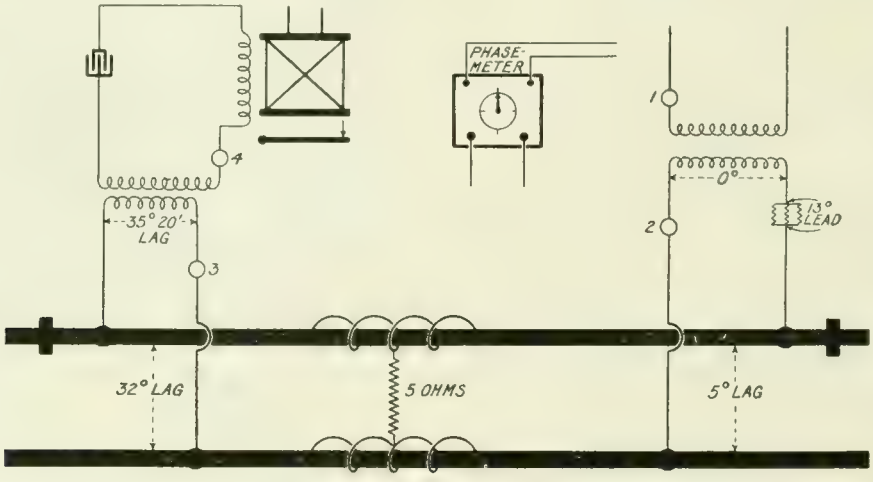

FIG. 29.—A.C. track circuit showing phase angle at various points

Fig. 29 shows the arrangement of the track circuit, the figures in circles denoting the points at which the following readings were taken.

	Volts	Amps.	Watts	Power Factor
(1) ..	83·9	0·54	26·5	0·586
(2) ..	0·59	1·205	0·6	0·844
(3) ..	0·58	1·105	0·4	0·624
(4) ..	15	0·027	0·1	0·245
(5) ..	67·3	0·44	8·4	0·284

The step-up ratio of the relay transformer in this case was 44 to 1, the capacity inserted between the relay transformer and the relay being 2 microfarads. It will be seen that the rail impedance on even this 1,000 feet of track accounts for a 27° lag in the track current. The relay operating as shown in Fig. 29 had a difference of 74° in the phase angle between local and track currents.

DIRECT-CURRENT EFFECT.

In cases where alternating-current track circuits are installed on electrified roads using the running rails for the propulsion return current, it is essential that the alternating-current apparatus should not be affected by direct current. Where single-rail track circuits are installed, the return traction current has two paths back to the power stations, as shown in Fig. 30. One path lies on the continuous return rail, and a parallel path is formed through the relay track-winding and back on to the continuous return rail. The resistance of this alternative path must be kept sufficiently high in relation to that of the continuous return rail to limit the direct current passing through the relay and transformer secondary windings to a value which will not affect the operation of the relay or transformer by saturation.

This protection may also be obtained by placing small impedance coils across the transformer secondary and across the relay, these coils having relatively large impedance but low ohmic resistance.

In double-rail track circuits with impedance bonds the question of saturation of transformer or relay does not arise, as the bonds are of sufficiently low resistance to prevent any appreciable difference in potential between the two rails. The bonds themselves, however, are in the direct-current return path, and their operation must not be affected by any ordinary variations of the return traction current.

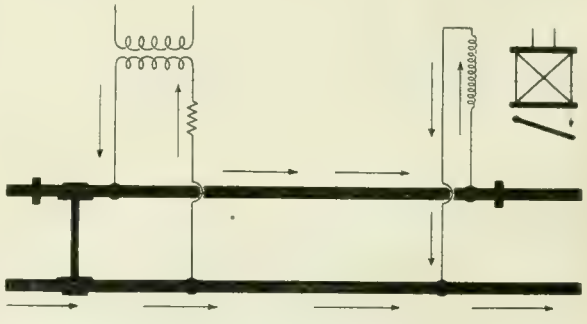

FIG. 30.—A.C. single-rail track circuit showing D.C. traction-current paths

As long as the return traction current is equally divided between the two rails, the effect on the iron of the bond caused by the current from one rail passing round one half of the bond winding will be neutralized by the current from the other rail passing round the other half of the winding in an opposing direction. Curves, check rails, and variations in rail section or material, all tend to cause a difference between the resistance of the two rails forming the section, and this results in more direct current traversing one half of the bond winding than the other. This direct-current magnetization may reach a point where the iron of the bond becomes saturated and the impedance of the bond to the alternating-current signalling current will then be decreased. To prevent saturation, the iron circuit of the bond is cut and an air-gap of variable thickness introduced. This reduces the impedance, but, provided the air-gap is of the correct length to provide for the maximum unbalancing current to be dealt with, the variations in impedance with lesser unbalancing currents will be small. This is necessary as any variation in the bond impedance will cause variations in the alternating voltage between the two track rails.

The impedance of a bond is to some extent dependent on the track voltage at which it is worked, the rise in impedance with the track voltage being of course more noticeable with the small air-gaps than with the larger.

Investigation has shown that the variation in impedance due to direct-current unbalancing of the bond is greater with the non-resonated type than with the resonated. In the non-resonated bond the impedance curves usually show a high peak, which falls rapidly as the unbalancing current increases. This peak can be flattened considerably if the air-gap can be increased, but the resulting low impedance of the bond prevents this remedy being of much use.

The impedance curves of a bond having a capacity of 750 amperes (D.C.) per rail are shown in Fig. 22. This bond was fitted with a condenser coil, but this was not connected during this test, so that the bond might be considered as of the ordinary non-resonated type. The tests were made at 50 cycles. It will be noted that with the 0·06 in. air-gap the impedance only rises slightly over a wide range of track voltage. The curves plotted above the impedance curves show the very low power factor of the non-resonated bond. The same bond was used to obtain the tests shown in Fig. 23, the condenser coil now being connected up and the number of turns in circuit in the coil being adjusted to give the bond as nearly as possible unity power factor. The air-gap was kept at 0·06 inch throughout the test. To enable a comparison to be made, the impedance curve of the non-resonated bond has been shown below that of the resonated bond, the air-gap, frequency and other conditions of the test being the same in each case. In both Fig. 22 and Fig. 23 it has been assumed that the direct-current propulsion return current in the two rails is equal. As previously stated this is not always the case and the bond impedance varies as the D.C. unbalancing current changes. The variation in impedance for different values of the d.c. unbalancing current is shown in Fig. 24. This curve was taken from the same resonated bond as that shown in Fig. 23. The alternating-current signalling supply was at 50 cycles and the bond air-gap 0·06 inch. A steady track voltage of 2·0 was maintained across the bond terminals. It will be seen from the curve that the power factor of the bond varies with the D.C. unbalancing current. If the bond is situated at a point on the line where there is always a certain amount of unbalancing current present, the drop in impedance can be overcome by altering the tapping of the condenser coil, thus making the bond have a leading power factor when no unbalancing exists, and the power factor then becoming unity when the pre-determined unbalancing current is present. The variation in impedance of the bond is less at lower frequencies than that shown, and at 25 cycles it is possible to build a resonated bond having less than 10 per cent variation in impedance between 0 and 200 amperes (D.C.) unbalancing current over a range of track voltages from 0·25 to 6 volts. Fig. 25 shows the impedance curves of such a bond, the solid line indicating the impedance without D.C. unbalancing current, and the dotted line the impedance with the maximum unbalancing current.

This variation in impedance, which appears to get greater as the frequency of the signalling current supply is increased, would appear to be due to the increase in the watt loss in the laminated core of the bond. It has been found that it is not advisable to reduce the volume of the iron in the bond core, as any step in this direction leads to two results, both of which are undesirable. Apart from the lower impedance of a bond with a small core, the watt loss which occurs if any attempt is made to increase the flux density in the core makes the bond inefficient; also the variation in impedance which occurs, particularly in bonds for the higher frequencies, gets greater as the core is made smaller. The normal working flux-density of these bonds is extraordinarily small, being in the neighbourhood of from 500 to 600 lines per square inch. It is only by working at such low densities as this that the bond losses on the alternating-current side can be kept small. The total alternating-current losses for a bond of the resonated type shown in Fig. 24 would be in the neighbourhood of 0·364 watt at 1·0 volt, rising to 1·4 watts at 2·0 volts across the track.

The keeping of these alternating-current losses low is of great importance, particularly in the resonated bond, as an increase in losses means a decrease in the impedance of the bond and an increase in the magnetizing current. Also, if the magnetizing current is increased, the condenser must be either made of larger capacity, or worked with a higher voltage across its terminals. It has been found desirable to limit the ratio between the number of turns in the condenser coil and the main coils of the bond, so that in the event of the full track-transformer secondary voltage being impressed on the bond, the alternating pressure across the condenser terminals does not rise above a predetermined figure, and spark-gaps are connected across the condenser to protect against any momentary surges due to any cause.

The necessity for using a large quantity of iron in the bond only applies in the case of direct-current

electrified roads where the heavy return traction current necessitates the bond having an air-gap to avoid saturation.

For steam-roads the bonds may of course be dispensed with entirely. Where an alternating current is used for traction the current in the return rails is usually very small and, even if one rail cannot be given up entirely for signalling purposes, bonds of much smaller capacity than those necessary to carry the return currents usually found on direct-current roads can be used. In some cases also the air-gap can be omitted and a closed iron circuit used. This results in a smaller and less costly bond than the heavy type used for direct-current traction. Wherever possible, bonds are placed between the track rails and short flexible copper leads are run from the bond terminals to the track rails. It is as well to remember that if the bonds cannot be placed centrally between the track rails they should be placed one on each side of the centre line, in order that the resistance of the copper leads may be the same for each half of the two bonds.

Reference has already been made in this paper to the utilization of the resonated bond as a means of improving the phase angle between the current in the track relay local and track windings. This method consists in varying the number of turns in circuit in the condenser coil of the bond until a tapping is found which gives the desired result on the relay. This variation of the condenser circuit of course varies the bond power-factor and in some cases is futile, and although the phase angle at the relay may be improved, the impedance of the bond may be decreased sufficiently to nullify the advantage of this improvement. If, however, it is found possible to vary the condenser in such a way that both the voltage across the relay track winding and the phase angle between the relay local and track currents are improved, then the adjustment is a good one, and improved shunting of the track and possibly a reduction in the track feed current will result. To obtain the best results from any double-rail track circuit with impedance bonds, it is necessary to make these adjustments when the track circuit is installed, and as nearly as possible under the normal working conditions of ballast resistance and unbalancing current, both the voltage across the relay and the phase angle being checked while the adjustment is being made.

Having considered the effect of direct current on the alternating-current impedance bonds, and the precautions taken to prevent failure of the bonds from this effect, we may now consider the effect of direct current on the relay. Relays of the galvanometer, vane or induction-motor type are all immune from operation by direct current, and the only effects of direct current on them are those which will cause the relay to drop—a "safe" failure, but one which must be guarded against to prevent traffic delays. If the relay is of the "in phase" galvanoneter type containing no iron, the direct-current effect is not marked and only adversely affects the relay as far as heating is concerned. Excess of direct current through the relay track winding may damage flexible connections to the moving armature, but otherwise this relay may be considered to be non-affected by direct current. The "quadrature" relays contain iron in some part or another and, if used for single-rail track circuits on direct-current electrified roads, must be protected against saturation from direct current passing through the parallel path shown in Fig. 31. In practice the relay is protected in a similar way to the track transformer by keeping the resistance up as much as possible, and it may also have an air-gap in its iron circuit which will assist in this protection.

Direct current has the same effect on this type of relay as on the impedance bond; that is, it decreases the impedance. Fig. 26 shows the fall in impedance when direct current is superimposed on a two-element vane relay working on alternating current. The centre curve shows the D.C. ampere-turns, and the dotted curves represent the A.C. ampere-turns added and deducted from the D.C. curve. The steady fall in impedance illustrates the necessity of protecting the relay against such direct-current interference. In the case illustrated the direct-current difference in potential across the relay track winding to give sufficient D.C. ampere-turns to put the relay out of action would be 0·55 volt. When installing this relay on a single-rail track circuit as shown in Fig. 30, it would be necessary to adjust the resistance of the parallel path formed by the transformer secondary, section rail and relay, so that this voltage would not be reached. The alternative method of protecting relays on single-rail track circuits by placing an impedance coil as a shunt across the relay has the disadvantage that it introduces an additional piece of apparatus into the track circuit, and this piece of apparatus having a different power factor from that of the relay may adversely affect the phase relationship desired between the relay track and local currents.

No mention has so far been made in this paper of the relays adopted for track-circuiting roads on which A.C. traction current is returned to the power house through both running rails. In such cases it is customary to adopt a higher frequency for the signalling current and to use a relay which is definitely selective and is therefore not operated by the lower-frequency traction current. Such relays, if of the two-element type, come under the same classification as that applied to all other two-element relays, namely, "in phase" or "quadrature," and are treated in the same way when constructing the track-circuit vector diagrams.

In conclusion the author would again emphasize the necessity of considering the apparatus forming an alternating-current track circuit as a whole and its operation under the varying conditions of ballast resistance, traction current and other factors which differ on every road. The large number of alternating-current track circuits installed in this country in recent years show great improvements over the earlier ones. There is little doubt that this progress will continue and that the very satisfactory results already obtained in operation will be more than maintained.

THE EFFECT OF SHUNTED RESISTANCE, OR PLUG LEAKAGE, ON THE SPARKING PERFORMANCE OF AN ELECTRICAL IGNITION SYSTEM.*

By G. E. Bairsto, D.Sc., D.Eng., Associate Member.

(*Paper first received* 6 *March, and in final form* 11 *May*, 1920.)

The work described in the following paper was carried out at the Royal Aircraft Establishment, Farnborough, during the years 1917–1918, and has been communicated to the Advisory Committee for Aeronautics as a confidential report. Permission for publication has now been granted by the Director of Research, Air Ministry.

Summary.

A description is given of a series of tests made to determine the effect of shunted resistance on the spark voltage of most of the leading types of electrical ignition systems in use. The effect of the alteration of some of the electrical constants is considered. It is shown that the quicker the rate of rise of the secondary potential the less is the fall of voltage with leakage. The order of merit of the various types is as follows:—

(1) Rotating armature types with movable pole-shoes.
(2) Ordinary rotating-armature types.
(3) Sleeve inductor types.
(4) Polar inductor types.
(5) Battery and coil systems.

A theoretical discussion is given in which formulæ are derived for the secondary voltage in the case of an ignition system shunted with a resistance of moderately low value. A number of curves are calculated for various cases. The actual measured values of the maximum voltage are shown to be in substantial agreement with these formulæ. It is also shown that to get the best possible results, the number of secondary turns should be made as small as possible. The effect of the coupling is considered and it is found that there is in each case a particular value of this factor which gives the maximum potential.

An appendix is given showing some tests of the leakage at high temperatures, and with high-tension current, of actual plugs that have missfired on engines. It is found that the average resistance of a spark plug that has run a moderately long time is about 200,000 ohms.

Introduction.

One of the most serious limitations imposed on an electric ignition system by the engine, especially an aero engine, is that after a sparking plug has run for some time it becomes a fairly good electrical conductor, due principally to the deposition of carbonized oil on the surface of the insulation and infiltration into the body of the insulation if of mica, and to burning-in of the glaze of porcelain insulation.

In a communication to the Advisory Committee for Aeronautics (Engine Sub-Committee Report No. 17) on the use of a series gap with leaky sparking plugs, it was shown that a resistance of the order of one megohm in parallel with a spark plug was sufficient to cause a falling off of the spark voltage of the magneto, and that if a resistance of about 200,000 ohms were used, a marked fall in the voltage was produced. These results were obtained on magnetos of the rotating armature and sleeve inductor types. The work now to be described is a more extended investigation into the effect of shunted resistance on the sparking performance of electrical ignition systems in general.

Apparatus and Methods.

In making the tests it was necessary to make a sharp distinction between the "regular sparking voltage" of a magneto and the voltage which only occasionally will give a spark. The latter may for convenience be called the "maximum sparking voltage." There is always a difference, sometimes very small and sometimes quite appreciable, between these two values, and it is usually attributable to imperfections in the contact breaker. In comparing two magnetos for spark voltages, it is the "regular sparking voltage" that matters and not the maximum voltage.

A cylinder fitted with a spark plug and pressure gauge was connected to a source of compressed air, which was continually renewed by being allowed to escape through a release valve at such a rate as to renew the air in the cylinder completely about three or four times a minute. This was done in order to prevent any complications due to the ionized air caused by the spark. The pressure was regulated and kept constant by means of a suitable stop-valve on the intake. The sparking plug was a K.L.G., C.B. type, having two crossed circular bars as spark points, and was chosen because it has a fairly small electrostatic capacity and the shape of the electrodes is such that "time-lag" is a minimum. The spark gap was kept constant at the standard figure of 0·015 inch. The method of test consisted in regulating the air pressure until the plug just ceased to miss sparking, the spark being viewed through a small window. In some cases the maximum voltage, and the corresponding air pressure, were also taken. The peak voltage across the plug was measured by means of a thermionic valve and a series electrostatic voltmeter in parallel with a highly insulated condenser. The variable leak consisted of a water

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resistance in the form of a U-tube, with variable electrodes.

In one or two cases, the safety gap was prevented from acting, but care was always taken that the magneto was allowed to relieve itself by sparking.

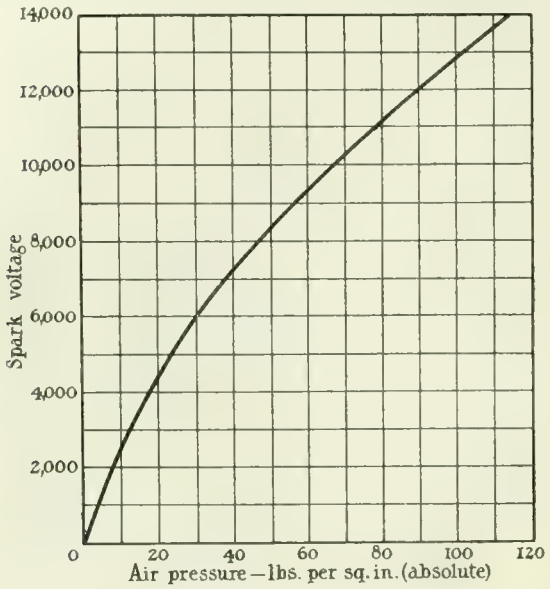

FIG. 1.—Relation between spark voltage of spark plug used in the tests and corresponding air pressure for regular sparking.

In presenting the comparative tests on different magnetos, it was found desirable to use air pressure for regular sparking as the ordinates of the curves because, from the point of view of the engine, this is the quantity which counts most. It should be pointed out that the relation between the spark voltage and air pressure is not quite the same for all types of ignition systems, and, moreover, the magnitude of the leak also affects the relationship. A curve shown in Fig. 1, which is a mean for various systems and leaks, gives the relation between the spark voltage of the plug and the air pressure, so that the results can approximately be converted to volts if necessary.

COMPARATIVE TESTS ON VARIOUS IGNITION SYSTEMS.

All the experimental results given in this section were taken at a constant magneto shaft speed of 1,800 r.p.m. except in the cases of the battery and coil sets, which were driven at a cam-shaft speed of 900 r.p.m.

Magneto No. 1 (*Six-cylinder*).—This magneto, of German origin, has a rotating armature and is fitted with movable pole-shoes in the form of a sleeve fitted into the armature tunnel. This sleeve is connected to the timing lever and moves with it in order to produce as nearly as possible equal spark voltage in both fully retarded and fully advanced positions.

Fig. 2 gives the results for both positions of the timing lever. The circles denote the air pressure for just regular sparking while the crosses give the results for just occasional sparking. The difference between the two values in this magneto is not very large. The arrows at the end of the diagram give the values of the air pressure for no leak. It will be seen that for resistances as low as one megohm there is little decrease in spark voltage, but below this figure it falls very rapidly.

Magneto No. 2 (*Six-cylinder*).—This machine is an English-made one and is also of the rotating-armature movable pole-shoe type. Although the maximum voltage is not quite so high as that of magneto No. 1, it does not fall quite so rapidly with large leaks.

Magneto No. 3 (*Six-cylinder rotating-armature machine of orthodox type*).—The results given in Fig. 3 are similar to the previous ones except that the voltage does not decrease quite so rapidly with increase of leak.

Magneto No. 4 (*Six-cylinder*).—This is a rather lighter model than the previous ones and has a smaller magnet. The results are similar to those given by magneto No. 3.

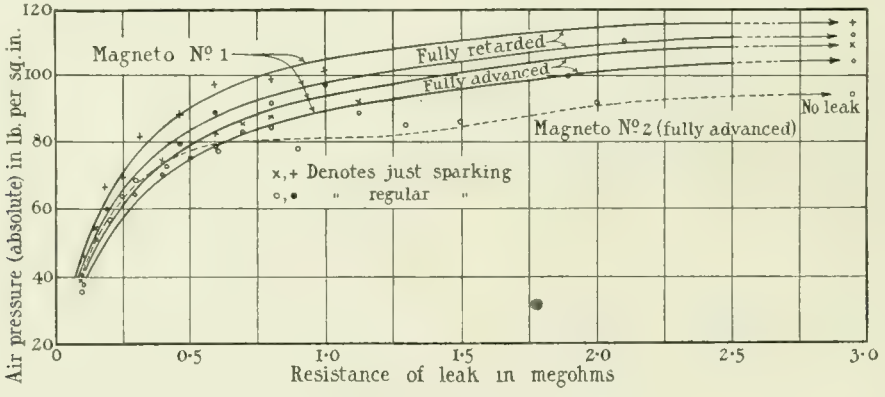

FIG. 2.—Magnetos of movable pole-shoe types.

Magnetos Nos. 5 *and* 6.—These machines are rotating-armature machines of very light-weight design with small armatures and small field-magnets. The former has a 7-way distributor fitted with a carbon brush. The latter has a 9-way distributor with a series jump spark approximately 0·012 inch in length. The results are also given in Fig. 3. Both magnetos give lower maximum pressures than either of the two previous ones; the general shape of the curves is, however, the same. It should be noted also that magneto No. 6

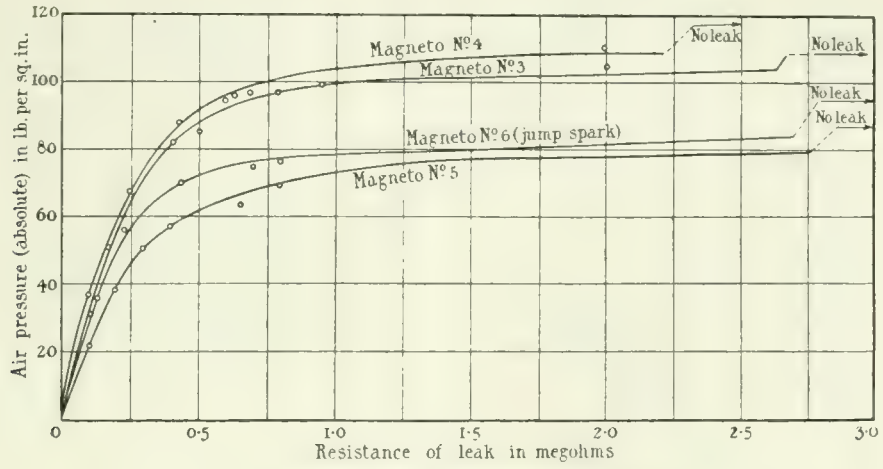

FIG. 3.—Magnetos of rotating-armature types.

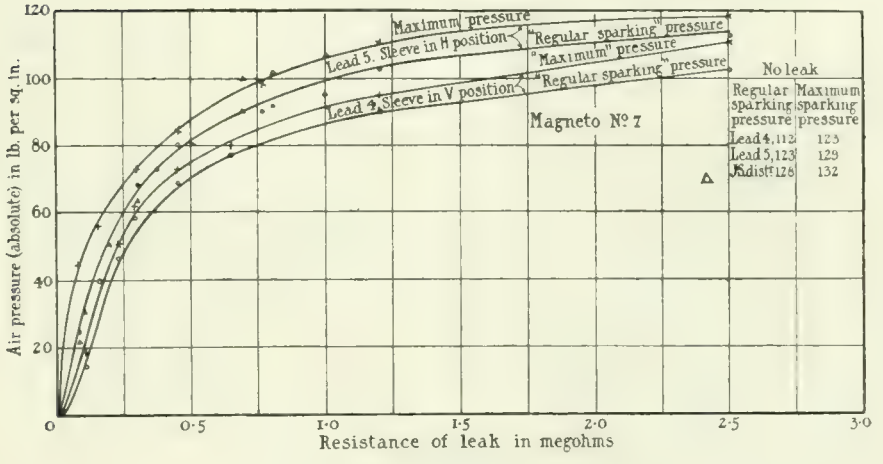

FIG. 4.—Magnetos of sleeve inductor type.
Jump spark distributor indicated thus: Δ.

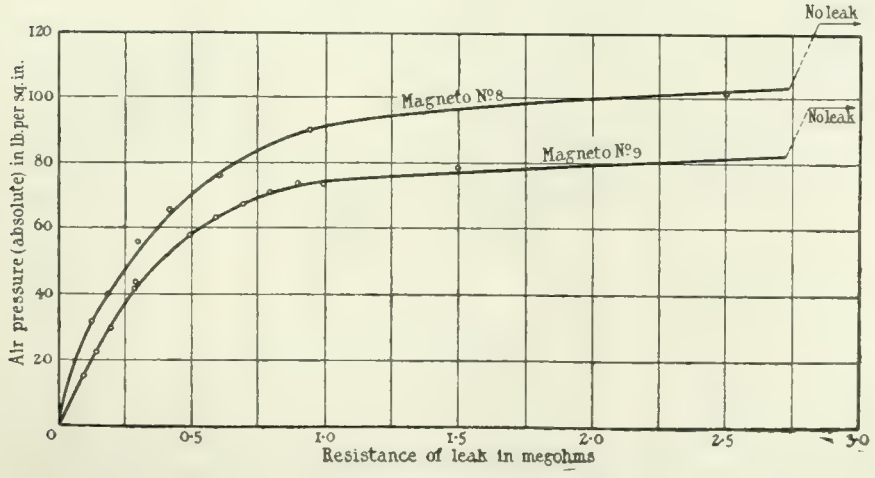

FIG. 5.—Magnetos of polar inductor types.

gives slightly better results, but this is probably due to it having a slightly stronger magnet. In any case the feeding of the spark through a short series gap of the size employed in this type of distributor effects little improvement on the leakage performance.

position. Results are given in Fig. 4 for both positions The shapes of the curves are the same. Some tests were also made with a jump spark distributor fitted instead of a carbon brush. The points so obtained are marked thus, Δ. It will be seen that practically no improve-

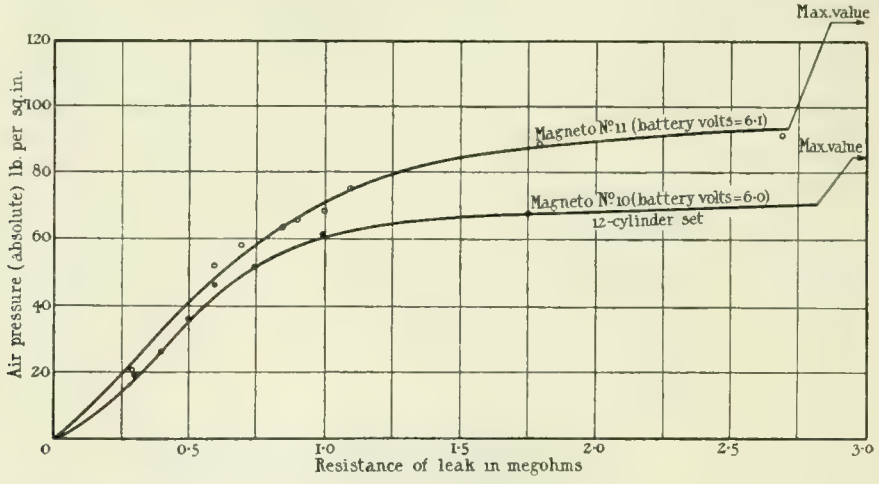

FIG. 6.—Coil and battery sets.

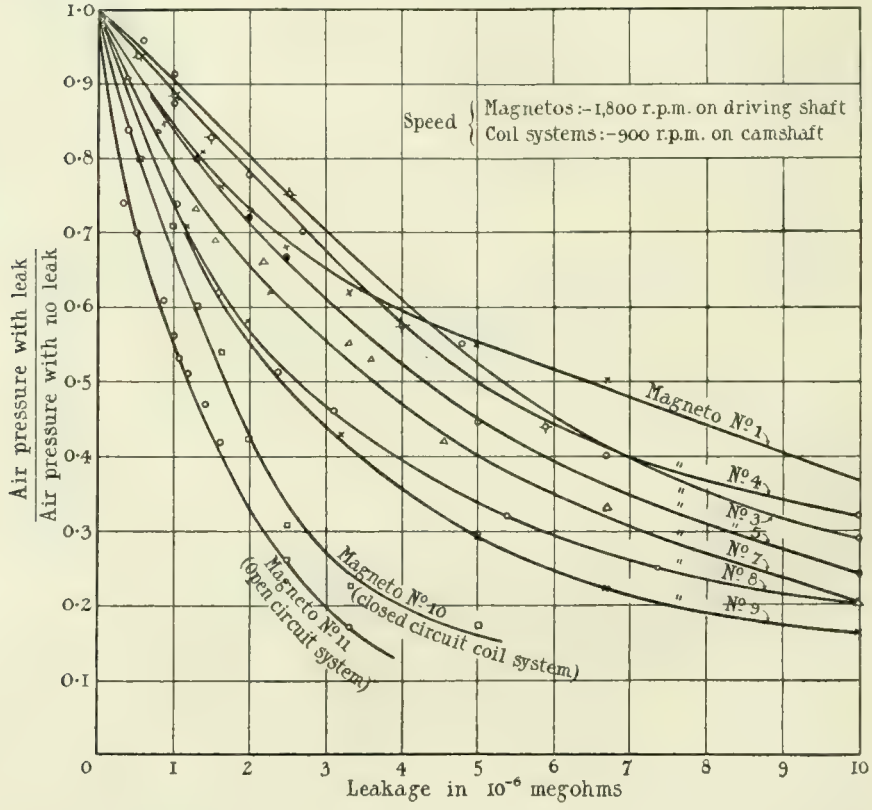

FIG. 7.—Relation between drop of air pressure and leakage for various ignition systems.

Magneto No. 7 (Eight-cylinder).—This magneto is of the sleeve inductor type. Alternating sparks are of different strength, the H-position of the sleeve at the "break" giving a greater voltage than the vertical

ment was made with the use of the series gap, confirming the previous results obtained on magneto No. 6.

Magneto No. 8 (Eight-cylinder).—This magneto is of the polar inductor type with a stationary armature.

Results are given in Fig. 5. Its performance is rather worse than that given by magneto No. 7.

Magneto No. 9 (Eight-cylinder).—This machine is similarly designed to the previous one but is much more lightly built. The results are given in the same diagram. With large leaks it is the worst of all the magnetos tested.

Coil and battery set No. 10 (Twelve-cylinder).—This set has a separate coil and a double contact breaker of the closed circuit type. Fig. 6 gives the results. It should be noted how very rapidly the pressure falls with increasing leakage, so that with half a megohm shunted across its terminals it would be quite incapable of firing the spark plug in the engine.

Coil and battery set No. 11 (Four-cylinder).—This set has a contact breaker of the open circuit type, i.e. it produces a spark at the " make " of the primary current. Although it starts off with a maximum pressure of 125 lb. per square inch, for no leak, as against the previous one with 85 lb. per square inch, the pressure falls very rapidly when the leak is of the order of 200,000 ohms.

Summary of Results.

We may compare the various systems in either of two ways:

(1) The actual air pressure for some particular value of the resistance shunting the spark plug.
(2) The ratio of the air pressure with some particular leak, to the air pressure with no leakage.

Table 1 gives a comparison made by method No. 1, the magnetos being arranged in their order of merit for a shunt resistance of 500,000 ohms.

Table 1.

Magneto	Type of Magneto	Air Pressure (with 500,000 Ohms in parallel with Plug)
		lb.
4	Rotating armature	92
3	Rotating armature	87
1	Rotating armature (movable pole-shoes)	77
2	Rotating armature (movable pole-shoes)	74
6	Rotating armature (light type with jump spark distributor)	72
8	Polar inductor	70·5
7	Sleeve inductor	70 and 81
5	Rotating armature (light type)	62
9	Polar inductor	58
10	Coil and battery	40
11	Coil and battery	41

The figures given in the third column will not be the same for each specimen of any particular type of design, chiefly because the strength of the magnets may vary from specimen to specimen, and in the table given above we are not making a fair comparison as the substitution of a stronger or larger magnet might turn an indifferent magneto into a good one. Method (2) would therefore seem to be a better criterion for comparison of *designs*.

Fig. 7 shows the results for the various magnetos compared on the basis of the ratio of air pressure with leakage, to the air pressure with no leak, the ordinates giving this ratio and the abscissæ the leakance, or the reciprocal of the shunted resistance. It should be noted that some of the curves cross one another: thus magneto No. 1, although rather worse than magneto No. 3 with comparatively small leaks, is distinctly better when the leakage becomes large. One very striking feature shown in the curves is the very indifferent performance of the battery and coil ignition systems. Table 2 conveniently summarizes the results:

Table 2.

Magneto	Type of Magneto	Ratio of Air Pressure with Leak of 100,000 Ohms to Air Pressure with no Leak
		Per cent
1	Rotating armature (movable pole-shoes)	36
2		36
4	Rotating armature (heavy type)	32
3	Rotating armature (heavy type)	29
6	Rotating armature (light type)	28·5
5	Rotating armature (light type)	23
7	Sleeve inductor	20*
8	Polar inductor	20
9		approx. 10
10	Coil and battery	,, 8
11		,, 5

It will be seen from the curves and the table that the magnetos group themselves fairly well in their main types of designs, and in the following order: rotating armature, sleeve inductor, polar inductor, and coil and battery. Also in the first class the machines with the movable pole-shoes are better than the others, while the heavy types of ordinary rotating-armature machines appear to be slightly better than the lighter types. The performance of the polar inductor machine is only roughly 50 per cent of that of the rotating-armature type, while coil and battery sets show up very badly. Actually the air pressure for leaks greater than 5×10^{-6} mhos was below that of the atmosphere and the values given in the table had to be extrapolated from the curves.

Effect of Alteration of Some of the Magneto Electrical Constants.

Effect of alteration of speed of magneto.—A series of tests were taken on a No. 1 magneto at various speeds for both no leak and for a leak of 100,000 ohms. Tests were made for the plug just sparking and also for perfectly regular sparking. The curves, which are shown in Fig. 8, are very similar. Table 3 gives the

* This value is the average for the sparks produced at the horizontal and vertical positions of sleeve.

ratios of the two pressures, with and without leak, the ratio being practically constant at low speeds, but falls off as the speed becomes large.

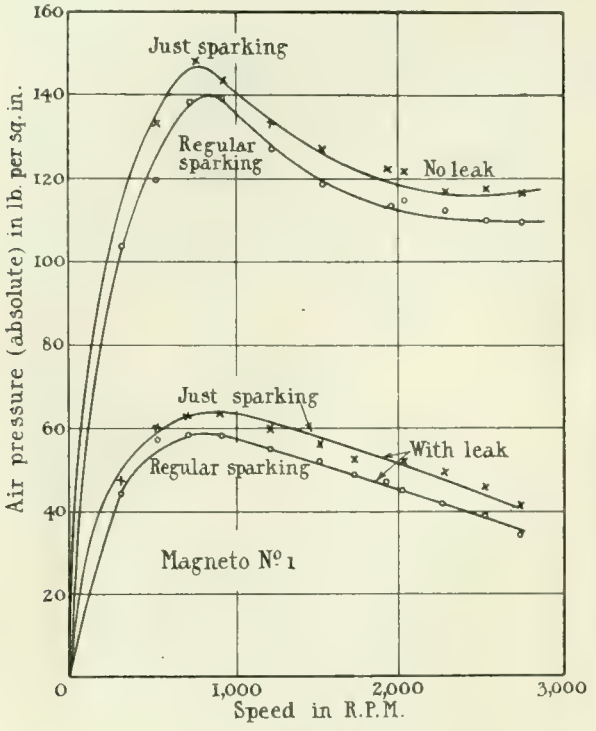

FIG. 8.—Effect of speed.
Leak = 100,000 ohms.

A similar set of results was obtained from a No. 9 magneto with 500,000 ohms in parallel with the plug. These results are given in Fig. 9 and Table 4. In this

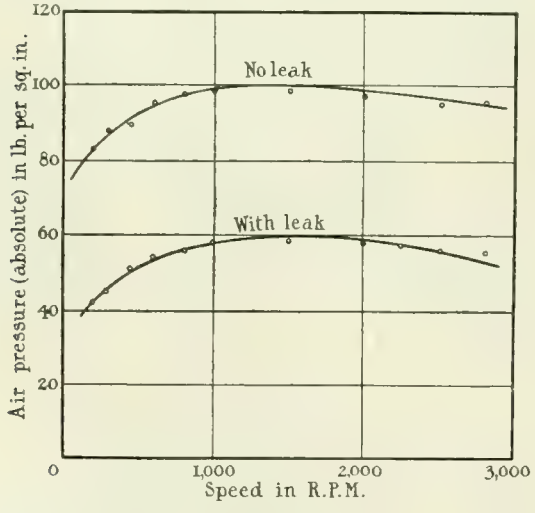

FIG. 9.—Effect of speed of magneto No. 9, with 500,000 ohms in parallel.

case the pressure ratio rises from 49 per cent at low speeds, to a maximum of 60 per cent, and then falls away again at top speeds to about 50 per cent.

Effect of alteration of primary capacity.—The effects under discussion will of course vary greatly with the electrical constants of the various machines, and, in order to understand more fully what is happening, a series of observations were taken in which one of these factors was varied over a fairly wide range and all the others were kept constant. All the results to be given now and in the remaining paragraphs of this section of the report were taken with a constant magneto speed of 1,800 r.p.m.

TABLE 3.

Effect of Speed on Magneto No. 1. Leak of 100,000 Ohms.

Speed in r.p.m.	Air Pressure with Leak / Air Pressure without Leak
300	0·42
500	0·47
700	0·42
900	0·46
1,200	0·47
1,500	0·45
1,900	0·40
2,000	0·39
2,250	0·37
2,500	0·35
2,700	0·32

TABLE 4.

Effect of Speed on Magneto No. 9. Leak of 500,000 Ohms.

Speed in r.p.m.	Air Pressure with Leak / Air Pressure without Leak
200	0·49
300	0·50
450	0·56
600	0·57
800	0·57
1,000	0·58
1,500	0·59
2,000	0·59
2,250	0·60
2,500	0·58
2,750	0·58
3,200	0·51

Fig. 10 shows how the spark voltage of a No. 9 magneto varies with the primary capacity, a series of curves being given for various leaks. The voltages as before are for just regular sparking of the plug under pressure. The no-leak curve, except for a tendency to form a hump near 0·2 mfd., gradually falls as the capacity increases. This result is similar to that shown by an induction coil. In the case of the 500,000-ohm leak, the fall of voltage is not at all as great and a

definite hump shows itself at 0·21 mfd. With the 200,000 ohm leak, the curve becomes practically flat except for a slight hump at the beginning. In the two lower curves, the initial hump appears to have disappeared and each curve consists of a gentle rise at the beginning, next a flat portion, and then the curve tends to fall again.

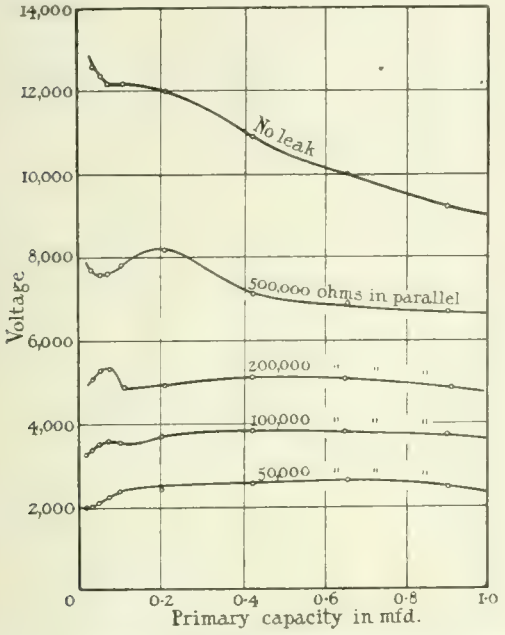

FIG. 10.—Variation with primary capacity of the secondary voltage (just regular sparking) in magneto No. 9.

It is of interest to see whether the condenser actually fitted to the magneto gives the best possible results. Its value is 0·096 mfd. The no-leak curve shows that a slightly better performance is obtained with smaller capacities than this, but such smaller capacities are not permissible, as it was found that sparking occurred at the contact-breaker points. The 100,000-ohm curve shows that with 0·2 mfd. an improvement of about 7 per cent can be effected. With the other curves the increase is not so apparent, but the whole tendency is for the best value of the capacity to be rather higher with a leak on the system, than it is for no leakage.

Effect of alteration of secondary capacity.—Some tests were made on a No. 9 magneto with various capacities shunted across the plug. The condensers were air plate condensers of negligible power factor. The results are shown in Fig. 11 where curves are given for two settings of the leak, viz. 1 and 0·1 megohm. All the curves are gradually drooping ones. The dotted curves give the ratio of the voltage with leak to that with no leak. They show that the percentage drop in voltage with a constant leak is practically independent of the value of the shunted capacity.

Effect of alteration of secondary inductance.—In order to test the effect of altering the secondary inductance, a No. 9 magneto was used and the current from this was fed to the spark plug via one or more secondary windings of some other magnetos of the same time. These latter machines had approximately the same inductance, and the rotor was fixed in each case so that the contact breaker was just open. Fig. 12 shows the results obtained with 1, 2, 3 and 4 windings in series. With no leak there was only a slight fall in the voltage, but as the leakage increased the drop became more marked. With the leak of 0·1 megohm the voltage became practically inversely proportional to the inductance. This is shown in the dotted curve which gives the product of the voltage and the number of windings.

Effect of alteration of primary resistance.—Table 5 gives the results of some tests made by inserting various amounts of resistance in series with the primary winding. As the resistance of the primary winding was only 0·71 ohm, and in few magnetos is the figure much higher, the results show that within moderate limits, say 0 to 2 ohms, the primary resistance has little influence on the spark voltage. Beyond 2 ohms the effect is much more marked, as the resistance then becomes comparable with the reactance of the winding.

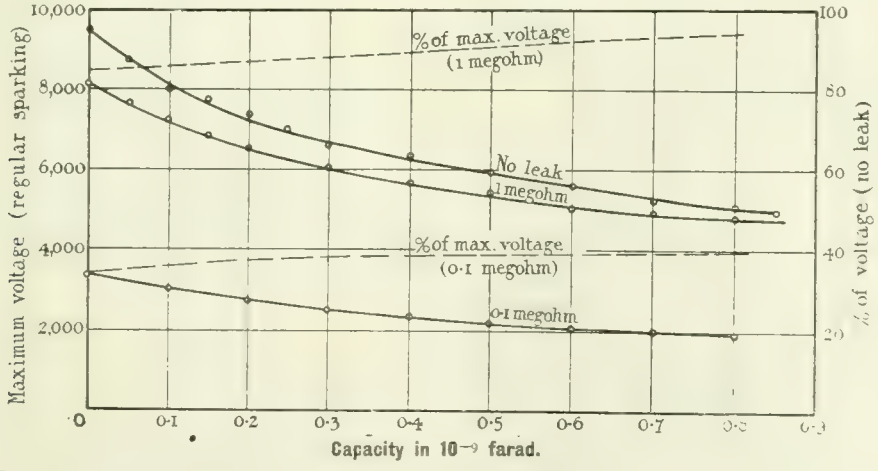

FIG. 11.—Variation with secondary capacity of the secondary voltage (magneto No. 9).

TABLE 5.

Effect of Alterations of Primary Resistance.
8-cylinder Magneto No. 9.

Added Resistance	Voltage for just Regular Sparking	
	No Leak	Leak = 1 megohm
ohms	volts	volts
0	10,300	8,300
1·0	10,200	8,100
2·5	9,700	8,000
4·0	9,100	7,300
5·0	8,700	7,000

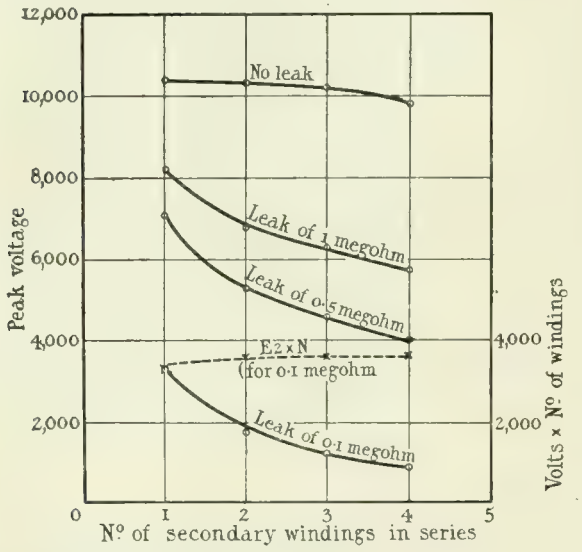

FIG. 12.—Effect on secondary potential of the variation of secondary inductance (magneto No. 9).

THEORETICAL DISCUSSION: THE RELATION BETWEEN $\frac{dV}{dt}$ AND THE FALL OF VOLTAGE.

The mathematical discussion of the secondary potential of an induction coil or magneto coil winding has been extensively developed by Oberbeck,* Rayleigh,† Dibberne,‡ and Taylor-Jones,§ but the case of a resistance in parallel with the spark gap does not seem to have been treated. It is, however, in its complete form, one of some complexity, and it would appear, so far as the author has carried it, to be so involved as to be of very little use for the purpose of calculation. A very simple calculation will, however, give some idea of the order of magnitude of the effect of shunt leakage.

* OBERBECK: *Wiedemann's Annalen*, 1897, vol. 62, p. 109.
† RAYLEIGH: *Philosophical Magazine*, 1901, vol. 2, p. 581.
‡ DIBBERNE: *Annalen der Physik*, 1913, vol. 40, p. 938.
§ TAYLOR-JONES: *Philosophical Magazine*, 1909, vol. 17, p. 28; 1911, vol. 22, p. 706; 1914, vol. 27, p. 565; 1915, vol. 29, p. 1; and 1918, vol. 36, p. 145.

The above-mentioned physicists have shown that the potential rises in the secondary as the result of two oscillations of different frequencies. In a magneto these frequencies are usually of different magnitudes, and the term with the largest amplitude has the lowest frequency. The potential therefore takes a finite time to reach its maximum value, and we may very approximately represent it by $E_0 \sin\frac{\pi t}{2 t_0}$, where t_0 is the time required for the potential to reach its maximum

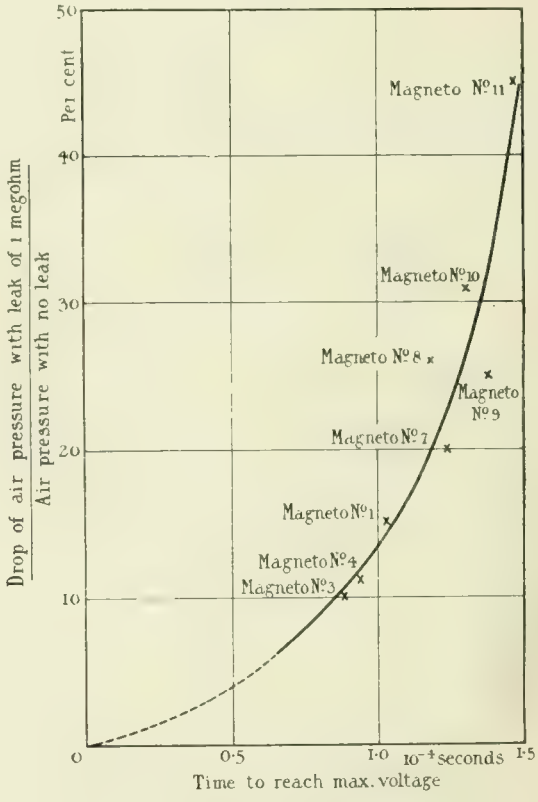

FIG. 13.—Relation between rate of rise of potential and percentage drop in air pressure with a leak of 1 megohm, for various types of ignition systems.

value. Let R be the resistance in parallel with the spark, then during the whole time that the potential is rising, current is leaking via the leak and the total energy so wasted is equal to

$$\frac{E^2}{R}\int_0^t \sin^2\frac{\pi t}{2 t_0}\, dt = \frac{E_0^2 t_0}{2R}$$

Now t_0 as found from rotary spark-gap tests is a quantity of the order of 10^{-4} seconds. Assuming therefore a spark potential of 10,000 volts and a shunt resistance of 100,000 ohms, the total energy wasted is equal to 0·05 joule. Now the whole energy in the spark discharge of even a very powerful magneto seldom exceeds 0·1 joule, hence a leak of the above magnitude would produce such a drain on the limited amount of energy available that the potential would never reach

10,000 volts. Hence the *rate of rise* of the secondary potential is of extreme importance when considering the efficiency of an ignition system as affected by plug leakage. The greater the rate of rise of potential, the larger is the leakage the system will stand before miss-firing.

It is therefore of interest to see how the effect of a small leak on the voltage is related to the rate of rise of potential of the various ignition systems under consideration. This relationship is depicted in Fig. 13, where the percentage drop in air pressure for a shunted resistance of 10^6 ohms, from that given with no leak, is plotted against the lag of the spark as measured on a rotary spark gap. This gap was set for a pressure of 12,000 volts, and the reciprocal of this lag therefore gives a measure of the mean rate of rise of potential from zero time up to this voltage.

Although all the points do not lie on the fair curve that has been drawn through them, the general nature of the results is quite clear. The shorter the time taken to reach the peak voltage, the less is the drop of voltage from its value when no leak is present. The differences between the actual points and the curve are easily accounted for by the fact that the potential waves are by no means similar in each case, and in some cases the wave has a large component due to the secondary rotational electromotive force.

Approximate Expressions for the Secondary Potential when the Leak is Large.

We have obtained in the previous section some idea of the effect a moderately small leak of the order of a megohm has on the secondary potential, but it is at present impossible to verify the results by calculation. In the case of a fairly large leak of the order of 10,000 ohms. however, we can obtain with no great difficulty an expression for the secondary spark potential. In this case the admittance of the secondary for currents having frequencies of the order of 10,000 periods, i.e. $C_2 p$, where C_2 is approximately 100 mfd. and $p = 2\pi \times 10{,}000$, is about 6×10^{-6} mhos, and may be neglected in comparison with the leakance produced by a shunt of 10,000 ohms or less.

Even with a shunt resistance as large as 100,000 ohms, calculations based on the assumption of $C_2 = 0$ will give a very good approximation, since the total admittance, that is, $[C^2 p^2 + 1/R^2]$ is only 18 per cent greater than 1/R. Moreover, the reactance of the winding, $L_2 p$, being of the order of $50 = 2\pi \times 10^4$, or 3×10^6 ohms, is so much larger than R that the presence, or otherwise, of a condenser of the above-mentioned capacity would have little effect on the phase difference between the current through the shunted resistance and the secondary electromotive force. We can therefore, with confidence, apply the expressions deduced below to cases of leaks up to 100,000 ohms. Fig. 14 then represents our scheme of circuits.

Let L_1 and L_2 be the values of the inductances of the primary and secondary winding respectively, C_1 the primary capacity, M the mutual inductance, and R_2 and R the resistances of the secondary winding and of the leak respectively.

The resistance of the primary will be neglected, as we shall be principally concerned with the initial rise of potential, and not with the subsequent stages of discharge. That is, we neglect the damping due to the primary resistance as having only a small effect on the maximum value of the potential. The experimental results already given in Table 5 justify this assumption.

Let E_p and E_s be the values, at the moment of "break," of the electromotive forces produced in the primary and secondary windings respectively by the

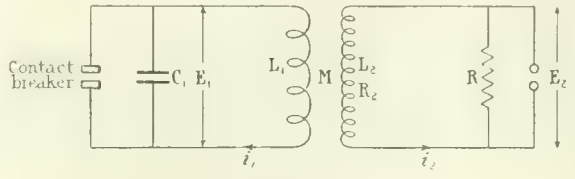

Fig. 14.

rotation of the armature, and E_1 and E_2 be the electromotive forces at the terminals of the primary capacity and of the spark plug respectively.

Then
$$L_1 \dot{i}_1 + M \dot{i}_2 + E_1 = E_p \quad . \quad . \quad . \quad (1)$$

$$L_2 \dot{i}_2 + M \dot{i}_1 + (R + R_2) i_2 = E_s \quad . \quad . \quad (2)$$

where
$$i_1 = C_1 \dot{E}_1$$

Eliminating i_2, E_1, E_p, and E_s from the above equations we have

$$\left(1 - \frac{M^2}{L_1 L_2}\right) \ddot{i}_2 + \left(\frac{R + R_2}{L_2}\right) \dot{i}_2 + \frac{1}{L_1 C_1} i_2 + \frac{R - R_2}{L_1 L_2 C_1} i_2 = 0 \quad . \quad (3)$$

Assume as a solution

$$i_2 = A e^{pt} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

Then p is given by

$$\left(1 - \frac{M^2}{L_1 L_2}\right) p^3 + \frac{R + R_2}{L_2} p^2 + \frac{1}{L_1 C_1} p + \frac{R - R_2}{L_1 L_2 C_1} = 0 \quad (5)$$

The complete solution of the equations is too complicated to give at present. Three extreme cases only will be indicated.

Case I. R small.*

We can neglect the second and fourth terms in equation (5). This gives

$$p^2 = -\frac{1}{L_1 C_1 (1 - k^2)} \quad \text{and} \quad p = 0 \quad . \quad . \quad (6)$$

where k^2 is the coefficient of coupling.

The secondary current consists therefore of two oscillatory terms, the frequency of which is given by

$$(2\pi n)^2 = q^2 = -p^2 = \frac{1}{L_1 C_1 (1 - k^2)} \quad . \quad . \quad (7)$$

Case II. R moderately large.

* L_2 is of the order of 30 to 50 henries, i.e. $L_2 p$ is about 3×10^6 ohms. Our original limitation of $R < 100{,}000$ therefore fits in with this case, as $R / (L_2 p)$ is $< 1/30$.

In this case we can neglect the first and third terms in equation (5). This gives

$$p^2 = -\frac{1}{L_1 C_1} \quad \ldots\ldots \quad (8)$$

Case III. $(1 - k^2) = 0$, i.e. for perfect coupling. In this case we have

$$p^2 + \frac{L_2 p}{L_1 C_1 (R + R_2)} + \frac{1}{L_1 C_1} = 0$$

i.e.

$$2p = -\frac{L_2}{L_1 C_1 (R + R_2)} \pm \sqrt{\left[\frac{L_2}{L_1 C_1 (R + R_2)}\right]^2 - \frac{4}{L_1 C_1}} \quad \ldots \quad (9)$$

(*a*) If $(R + R_2) > L_2/\sqrt{(L_1 C_1)}$, the current waves are oscillatory and have a frequency given approximately by

$$(2\pi n)^2 = q^2 = \frac{1}{L_1 C_1}$$

(*b*) If $(R + R_2) < L_2/\sqrt{(L_1 C_1)}$, the current waves each consist of two terms following an exponential law with respect to time.

Only Case I and Case III (*b*) need be developed, i.e. for the case of a very leaky sparking plug.

Development of Case I.—We may write

$$i_1 = U_1 \epsilon^{p_1 t} + V_1 \epsilon^{p_2 t} + W_1 \epsilon^{p_3 t} \quad \ldots\ldots \quad (10)$$

$$\text{and} \quad i_2 = U_2 \epsilon^{p_1 t} + V_2 \epsilon^{p_2 t} + W_2 \epsilon^{p_3 t} + \frac{E_s}{R + R_2} \quad (11)$$

where p_1, p_2, p_3 are the roots of equation (5).

As indicated, the first approximations to these roots are 0, qj, $-qj$. These approximations neglect the damping. A second approximation may be written

$$\left.\begin{aligned} p_1 &= -a + qj \\ p_2 &= -a - qj \\ p_3 &= c \end{aligned}\right\} \quad \ldots\ldots \quad (12)$$

$$\therefore (p - p_1)(p - p_2)(p - p_3) = 0$$

$$-(p + a - qj)(p + a + qj)(p + c)$$

$$\therefore p^3 + p^2(2a + c) + p(a^2 + q^2 + 2ac) + c(a^2 + q^2) = 0 \quad (13)$$

Comparing the coefficients of p^2 and p^0 with those of equation (5) we have

$$2a + c = \frac{R + R_2}{L_2} \cdot \frac{1}{1 - k^2}$$

$$c(a^2 + q^2) = \frac{R + R_2}{L_1 L_2 C_1} \cdot \frac{1}{1 - k^2} = \frac{R + R_2}{L_2} q^2$$

Now q is of the order of 10^4 and $(R + R_2)/L_2$ is by hypothesis never greater than 100,000 $\div L_2$, i.e. about 2,000 or less. We can therefore neglect a^2 in comparison with q^2

$$\therefore c = \frac{R + R_2}{L_2} \quad \ldots\ldots \quad (14)$$

$$a = \frac{R + R_2}{2 L_2} \cdot \frac{k^2}{1 - k^2} \quad \ldots\ldots \quad (15)$$

Substituting (10) and (11) in (2) we obtain an identity which must be satisfied for all values of t, and therefore we must separately have

$$\left.\begin{aligned} M p_1 U_1 + (L_2 p_1 + R + R_2) U_2 &= 0 \\ M p_2 V_1 + (L_2 p_2 + R + R_2) V_2 &= 0 \\ M p_3 W_1 + (L_2 p_3 + R + R_2) W_2 &= 0 \end{aligned}\right\} \quad (16)$$

Now $L_2 p_1$ and $L_2 p_2$ are $\gtrless (R + R_2)$, and

$$(L_2 p_3 + R + R_2) = 0$$

$$\left.\begin{aligned} \therefore \frac{U_1}{U_2} &= \frac{V_1}{V_2} = -\frac{L_2}{M} = \alpha \\ \text{and} \quad W_1 &= 0 \end{aligned}\right\} \quad \ldots\ldots \quad (17)$$

The constants U_1, V_1, W_1 are determined by the conditions that at $t = 0$, $i_1 = I_0$, $i_2 = E_s/(R + R_2)$, and $E_1 = E_p$.

The first two give

$$I_0 = U_1 + V_1$$
$$0 = U_2 + V_2 = W_2$$

The third gives by supplying (10) and (11) in (1) and putting $t = 0$ in the resulting expression,

$$L_1 (U_1 p_1 + V_1 p_2) + M (U_2 p_1 + V_2 p_2 + W_2 p_3) = 0$$

Hence we have

$$\begin{aligned} \alpha U_2 + \alpha V_2 + 0 &= I_0 \\ U_2 + V_2 + W_2 &= 0 \\ p_1 U_2 (M + L_1 \alpha) + p_2 V_2 (M + L_1 \alpha) + p_3 W_2 &= 0 \end{aligned}$$

The solutions are

$$U_2 = -\frac{M I_0}{2 L_2}\left[1 - \frac{R + R_2}{L_2 q} \cdot \frac{1 - k^2/2}{1 - k^2} j\right]$$

$$V_2 = -\frac{M I_0}{2 L_2}\left[1 + \frac{R + R_2}{L_2 q} \cdot \frac{1 - k^2/2}{1 - k^2} j\right]$$

$$W_2 = \frac{M I_0}{L_2}$$

Supplying in (11) and re-writing in terms of $\cos qt$ and $\sin qt$ we have

$$i_2 = \frac{E_s}{R + R_2} + \frac{M I_0}{L_2}\left[\epsilon^{-ct} - \epsilon^{-at}\left\{\cos qt - \frac{R + R_2}{L_2 q} \cdot \frac{1 - k^2/2}{1 - k^2} \sin qt\right\}\right] \quad (18)$$

The $\sin qt$ term is only of importance if k^2 is very nearly equal to unity and $(R + R_2)/(L_2 q)$ large. We can therefore in most cases neglect it. Putting $E_2 = R i_2$ we have

$$E_2 = \frac{R}{R + R_2} E_s + \frac{M I_0 R}{L_2} [\epsilon^{-ct} - \epsilon^{-at} \cos qt] \quad (19)$$

E_2 has its maximum value at a time t_0, where t_0 is given approximately by $t_0 = \pi/q$

$$\text{i.e.} \quad [E_2]_{\max.} = \frac{R E_s}{R + R_2} + \frac{M I_0 R}{L_2} [\epsilon^{-c\pi/q} + \epsilon^{-a\pi/q}] \quad (20)$$

In applying this to the case of a magneto winding, it should be noticed that after the "break" of the primary current, the secondary is in series with the primary. The effect of this may be approximately

allowed for by putting $M + L_1$ for M, and $L_2 + L_1 + M$ for L_2 in equation (20). Since, however, M is usually about 50 to 100 times larger than L_1, and L_2 bears about the same ratio to M, we may neglect the above correction.

Development of Case III (b). $(1 - k^2) = 0$.

We have $$i_1 = A_1 \epsilon^{at} + B_1 \epsilon^{bt}$$
$$i_2 = A_2 \epsilon^{at} + B_2 \epsilon^{bt} + \frac{E_s}{R + R_2}$$

where
$$(a, b) = \frac{-L_2}{2L_1C_1(R + R_2)} \pm \sqrt{\left\{\frac{L_2}{2L_1C_1(R + R_2)}\right\}^2 - \frac{1}{L_1C_1}}$$

Substituting these values in (1) and (2) we obtain an identity which must be satisfied by all values of t, and therefore we must separately have

$$M A_1 = C_1(R + R_2) L_1 a A_2$$
$$M B_1 = C_1(R + R_2) L_1 b A_2$$

The constants A_1, B_1, A_2, B_2 are determined by the initial conditions $t = 0$, $i_1 = I_0$, $i_2 = E_s/(R + R_2)$,

$$\therefore I_0 = A_1 + B_1 \quad \text{and} \quad 0 = A_2 + B_2$$

i.e. $$A_2 = -B_2 = \frac{M I_0}{L_1 C_1 (a - b)(R + R_2)}$$

As $L_2/(R + R_2)\sqrt{(L_1 C_1)}$ is $\gtrless$ unity we have the simplified expressions

$$a = -\frac{R + R_2}{L_2}$$
$$b = \frac{-L_2}{L_1 C_1 (R + R_2)}$$

or

$$E = \frac{E_s R}{R + R_2} + \frac{M I_0 R}{L_2}\left[\epsilon^{-t(R+R_2)/L_2} - \epsilon^{-tL_2/[L_1C_1(R+R_2)]}\right] \quad . \quad (21)$$

E_2 has its maximum value at $t = t_0$ when

$$a\epsilon^{at_0} = b\epsilon^{bt_0}$$

or
$$t_0 = \frac{1}{b}\log\frac{b}{a}$$

i.e. $$[E_2]_{max.} = \frac{E_s R}{R + R_2} + \frac{M I_0 R}{L_2}\left[\left(\frac{a}{b}\right)^{a/b} - \frac{a}{b}\right] \quad . \quad (22)$$

Both terms in the bracket are less than unity and their difference rapidly decreases as $\left(\frac{R + R_2}{L_2}\right)^2 L_1 C_1$ increases.

Curves Illustrating the Mathematical Discussion.

In order to make the mathematical discussion clearer a number of E.M.F. curves have been worked out for various values of the electrical constants. In all the cases to be considered no account is taken of the rotational electromotive force.

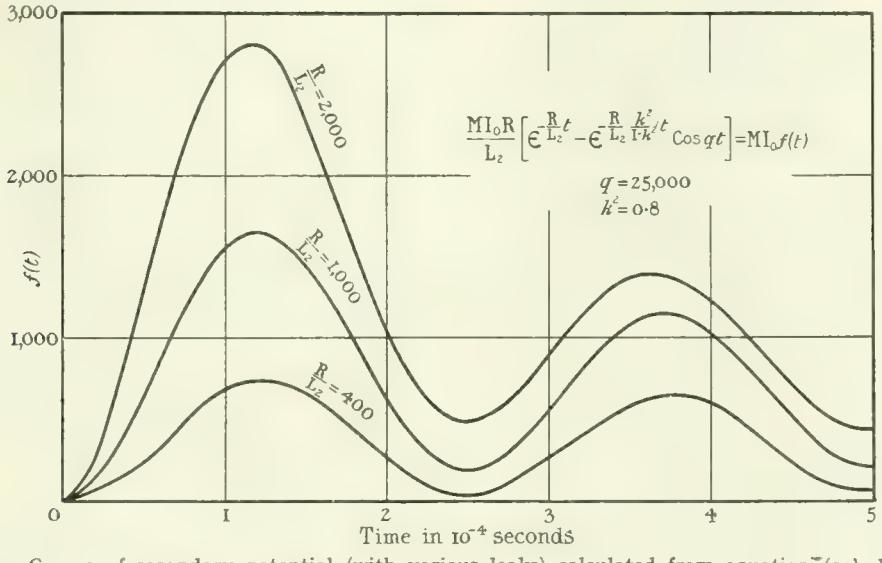

Fig. 15.—Curves of secondary potential (with various leaks) calculated from equation (19), $k^2 = 0{\cdot}8$.

Fig. 15 presents three curves calculated from equation (19), k^2 has been chosen as 0·8 and $q = 25{,}000 = 2\pi n$. The ordinates represent the voltages corresponding to unit M and unit I_0. The curves are very rapidly damped, and this damping naturally increases as R/L_2 increases. The points of maximum electromotive force practically coincide with those of $(1 - \cos qt)$.

In Fig. 16, k^2 has been kept constant as before at 0·8; R/L_2 is also constant at a value of 2,000; and a series of curves drawn for different values of the frequency or q.

As before, the ordinates give the volts for unit M and unit I_0. It should be noticed how rapidly the height of the initial peak falls as the frequency decreases. This is more clearly shown in Fig. 17, where the maximum values of E_2 as deduced from Fig. 16 are plotted against q. In Fig. 16, all the waves are bounded by the two exponential terms of equation (19), the top curve corresponding to the limiting value of $q = \infty$, and the lower one to the limiting value of $q = 0$.

The greater the resistance of the leak the more does the drop of potential depend upon the frequency. If the leak resistance is small the potential is controlled almost entirely by the ratio $M I_0 R/L$. This is easily seen by inspection of equation (20). The quantity in the bracket may be written approximately

$$[\epsilon^{-\pi c q} + \epsilon^{-\pi a q}] \doteq 2 - \frac{\pi}{q}(c + a)$$

$$\doteq 2 - \frac{\pi}{q}\left(\frac{R + R_2}{L_2}\right)\left(1 + \frac{1}{1}\frac{\frac{1}{2}k^2}{k^2}\right)$$

The factor involving k^2 varies in ordinary ignition systems between 1·5 and 3. Hence if $R + R_2$ is only about 1/300th of $L_2 q$, the above expression will only differ from 2 by about 1 per cent.

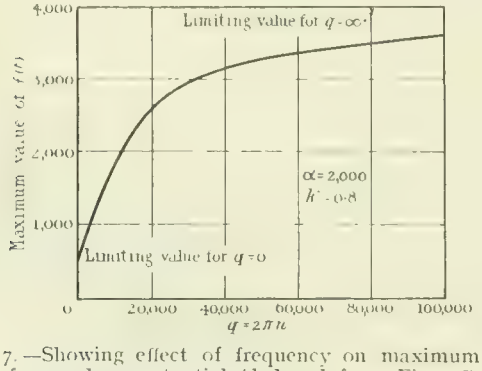

FIG. 17.—Showing effect of frequency on maximum value of secondary potential (deduced from Fig. 16).

To show how the results vary with the degree of coupling between the primary and secondary windings, the curves in Fig. 18 have been drawn for various values of k^2. The other constants have been supposed to vary so as to keep the frequency constant. As the coupling increases, the peak value of $f(t)$ decreases, and when k approaches unity, becomes only about half the value it has when k is very small. The maximum values of $f(t)$ have been plotted in the upper curves of Fig. 19. This curve shows the interesting feature that at a certain k^2 very nearly equal to unity, $f(t)$ is actually smaller than when $k^2 = 1$. It is, however, not a very practicable case.

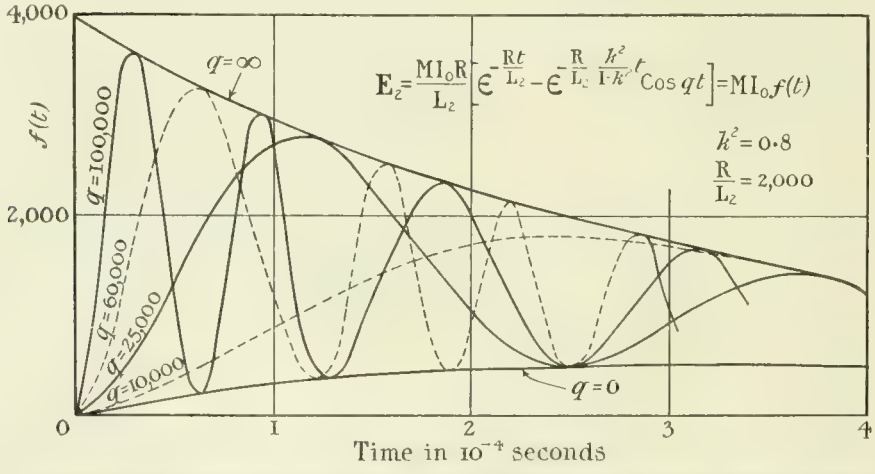

FIG. 16.—Curves of secondary potential E calculated from equation (10), showing effect of frequency, $q = 2\pi n$.

In the last paragraph we have only considered the variation of $f(t)$ with k^2. In order to see how the maximum voltage varies with k^2, we should use the product of k and $f(t)$, as M will be proportional to

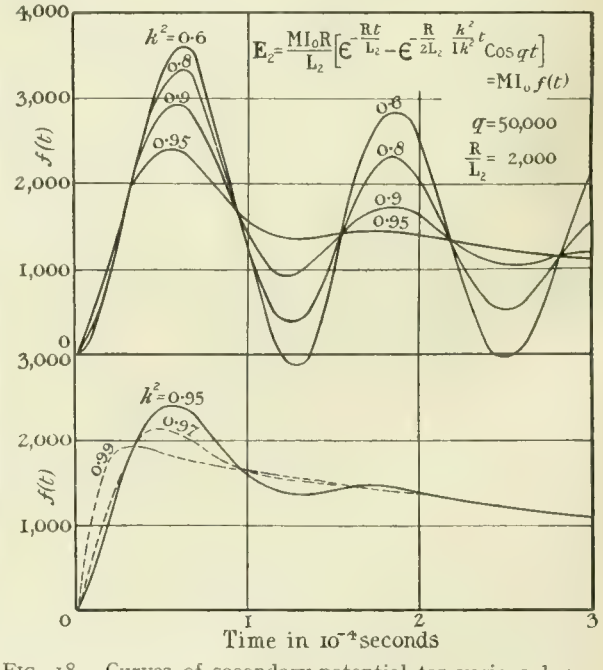

FIG. 18.—Curves of secondary potential for various degrees of coupling, as calculated from equation (19), $q = 50{,}000$. Constant leak.

k, L_1 and L_2 being kept constant. The variation of this quantity is shown in the lower curve. It will be seen that it has a maximum value at about $k^2 = 0{\cdot}8$, but the curve is fairly flat over quite a wide range.

In the limiting case of $k^2 = 1$, the curves are much simpler, as there are of course no oscillations. Four typical curves are given in Fig. 20. The greater is R/L_2, the greater is the damping. Comparison of the curves

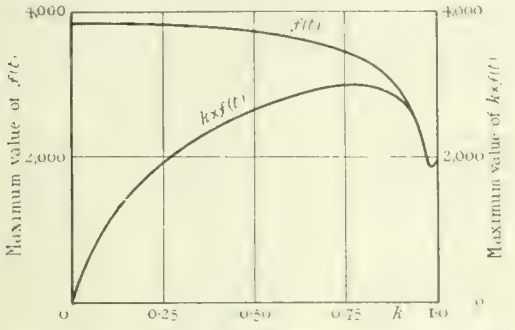

FIG. 19.—Variation with k^2 of maximum values of $f(t)$ and $f(t) \times k$. (Values taken from Fig. 18.)

with those of Fig. 15 shows that for the same R/L_2 the voltage is practically only half what it is when the electromotive force is built up by means of an oscillation.

COMPARISON OF CALCULATED WITH MEASURED VALUES OF SECONDARY POTENTIAL.

The general conclusions from the above theoretical discussion are in substantial agreement with the experimental results. Thus both theory and experiment agree as regards the beneficial effect of having as high a frequency as possible. Again Fig. 12, showing the effect of altering L_2, is in direct agreement with the conclusion that E_2 is inversely proportional to L_2 when the leak is large. As regards the effect of capacity, increasing either C_1 or C_2 decreases the frequency and therefore should decrease the voltage. In Fig. 11 this effect is observed, but in Fig. 10 it is not so marked. Still the general tendency of all the curves is downwards.

We shall now take an actual magneto and compare its calculated performance with its measured one. The machine used was a British Thomson-Houston A.V.8 inductor-type magneto with fixed ignition. It had the following electrical constants :—

$L_1 = 0{\cdot}0078$ henry at 3 amperes,
$L_2 = 28$ henries at 50 milliamperes,
$M = 0{\cdot}415$ henry at 3 amperes in primary,
$C_1 = 0{\cdot}20 \times 10^{-6}$ farads,
$R_2 = 16{,}500$ ohms.
$\therefore k^2 = 0{\cdot}78$; $q = 54{,}000$;
also $I_0 = 3{\cdot}75$ amperes.

All the inductances were measured with "break" currents of the amounts stated. It should, however, be mentioned that, for accurate calculation, we should really use the values obtained with high-frequency currents having frequencies of the order of 10,000. We are mainly concerned, however, with the ratio M/L_2, which may be assumed to be independent of the frequency, and the effect of the alteration of L_2 with frequency will be neglected in calculating q.

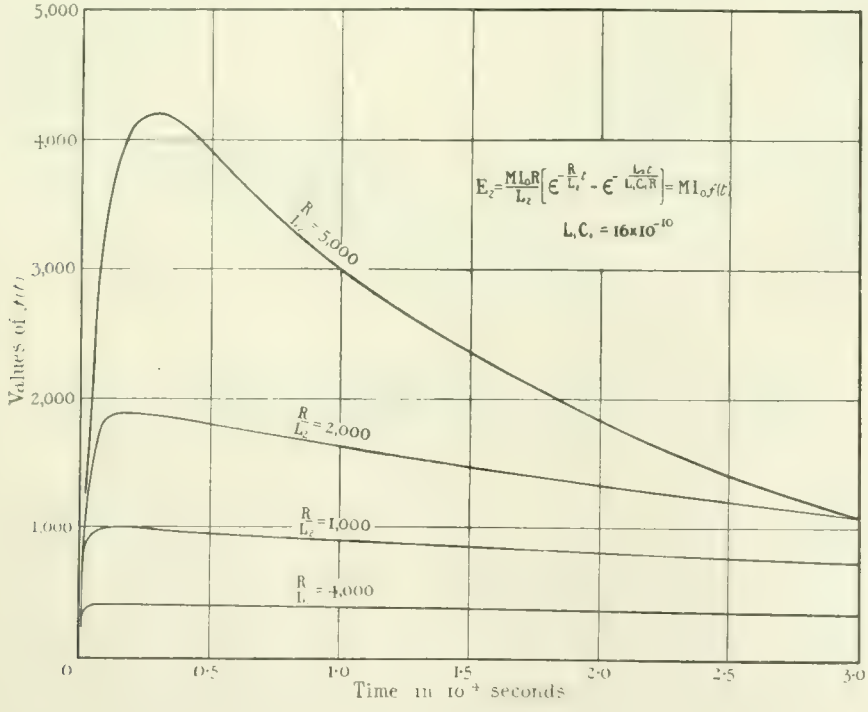

FIG. 20.—Curves of secondary potential with various leaks calculated from equation (21).
Perfect coupling, $k^2 = 1$.

R_2 was measured by a bridge method at a frequency of approximately 500 cycles per second.

Table 5 gives the calculated and measured results. The results are also shown graphically in Fig. 21.

E_B was calculated from equation (20), whilst E_R was obtained from the wave shape of the secondary electromotive force of rotation and is that ordinate of the wave which corresponds to the time at which the primary "break" occurs.*

With low resistances the agreement between the experimental and calculated figures is very good, the difference at 10,000 ohms being only 11 per cent. With higher resistances the differences are more marked; but seeing that only approximate values of L_1 and L_2 have been used, the differences are no more than were to be expected.

Magneto.—The total electromotive force of the machine may be written

$$E_2 = E_B + E_R$$

where the first term is due to the "break" of the primary current and the second one is the secondary rotational electromotive force. We shall, for the moment, neglect the effect of frequency and assume this to be sufficiently great, so that we get the maximum effect, or

$$E_B = \frac{2 M R I_0}{I_2}$$

TABLE 5.

Resistance of Leak	E_B Calculated	E_R Measured	E_2 (calculated) $= E_B + E_R$	E_2 Measured	Difference
ohms	volts	volts	volts	volts	per cent
100,000	7,400	720	8,120	5,050	31
75,000	6,050	650	6,700	4,700	30
50,000	4,350	520	4,870	3,650	25
25,000	2,350	360	2,710	2,250	17
10,000	970	210	1,180	1,050	11
5,000	500	140	640	580	9

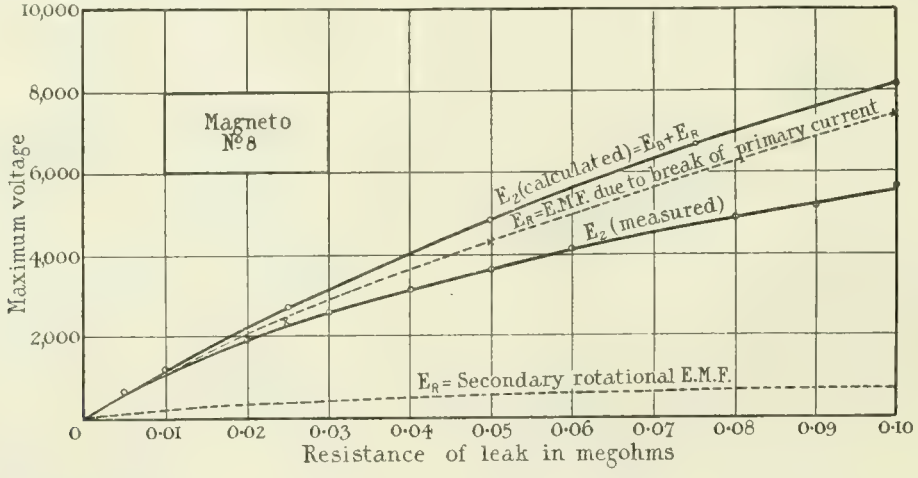

FIG. 21.—Relation between calculated and measured secondary potentials for various leaks.

Further work on this matter will have to be reserved until accurate methods of measuring the various inductances with moderately high-frequency currents have been devised and the variations of these quantities with current have been studied.

SOME APPLICATIONS OF THE PREVIOUS RESULTS TO THE DESIGN OF AN IGNITION SYSTEM.

We shall now see what help the above theoretical discussion gives us in designing the windings of an ignition system.

Let Φ = the flux through the armature core,
N_1 and N_2 = the primary and secondary terms respectively,
l = the length of the armature windings,
v = the average peripheral speed of the windings.

Then we may write $L_1 = \alpha_2 N_1^2 l$,

$L_2 = \beta^2 N_2^2 l$,

and $M = \alpha\beta N_1 N_2 l k$.

Also very approximately we may neglect the effect of the resistance of the primary and put

$$I_0 \propto \frac{E_p}{L_1 p} \propto \frac{\Phi N_1 v l}{a^2 N_1^2 p l} \propto \frac{\Phi}{a^2 N_1} = \frac{\lambda \Phi}{a^2 N_1}$$

* The wave shape was obtained by means of the author's high-speed synchronous contact maker.

where λ depends upon the geometrical configuration of the magnetic circuit.

$$\therefore E_B = \frac{2a\beta\lambda N_1 N_2 k l R\lambda\Phi}{\beta^2 N_2^2 l a^2 N_1} = \frac{2\lambda}{a\beta}\cdot\frac{k}{N_2}R$$

Also approximately

$$E_R \propto \Phi_2 N_2 c l = C N_2 n l \phi$$

where C is a constant.

$$\therefore E_2 = \left[\frac{2\lambda}{a\beta}\cdot\frac{k}{N_2}R + N_2 n l C\right]\Phi$$

so that for any fixed speed, E_2 may be written

$$E_2 = \left[a\frac{k}{N_2}R + bN_2 l\right]\Phi$$

In this expression *a* depends only on the magnetic circuit, while *b* is a function of the shunt resistance. The variation with R of the peak secondary rotational electromotive force is shown in Fig. 22 for several representative types of magnetos. The curves show only a gradually falling voltage down to about 20,000 ohms, after which the rate of fall is much faster.* On the other hand E_B is practically proportional to R. There is therefore some particular small value of R at which the two curves cross one another and E_R becomes of more importance than E_B. It is partly for this reason that magnetos are much better than the battery and coil systems, inasmuch as their electromotive force starts off with the initial advantage of having a large component which is not unduly affected by the leak.

Returning to the above expression for E_2 and considering only the main component E_B, we have the following results :—

(1) E_B is directly proportional to the coupling.
(2) E_B is inversely proportional to number of secondary turns.
(3) E_B is independent of the number of primary turns.

We assumed in the beginning that for a maximum effect *q* was large. This may be obtained by varying either L_1, C_1, or *k*, by making the first and second as small as possible or the third as large as possible, always bearing in mind, however, that there is an upper limit to *k* above which E_B decreases again.

Battery and coil systems.—Here the primary electromotive force is constant and equal to E. Very approximately we have

$$I_0 \propto \frac{E}{L_1 p}$$

$$\therefore E_2 \propto \frac{a\beta N_1 N_2 l k}{\beta^2 N_2^2 l}\cdot\frac{E}{a^2 N_1^2 p}R$$

$$\therefore E_2 \propto \frac{E}{a\beta l p}\cdot\frac{k}{N_2 N_2}R$$

In both cases therefore it is important that N_2 be made as small as possible.* This result it should be noticed is contrary to that required for obtaining the maximum potential when there is no leak on the system. In the latter case it is desirable to make the number of secondary terms as large as possible.

It must be clearly understood that the expressions obtained above are only to be regarded as first approximations. They can therefore be used only as a guide

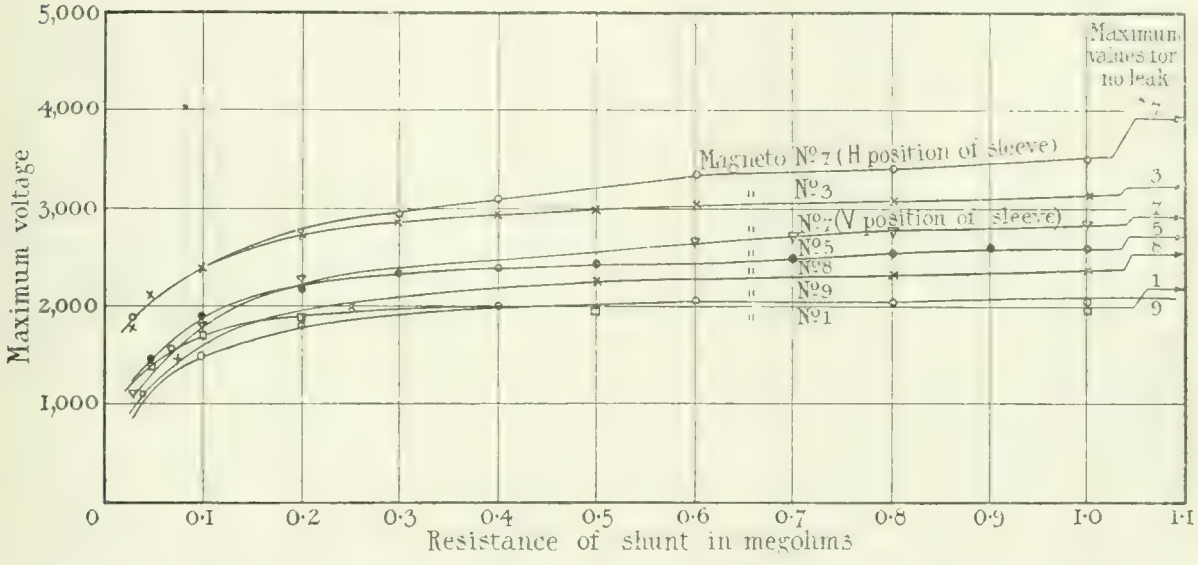

FIG. 22.—Effect of leakage on secondary E.M.F. of rotation.

Speed 1,500 r.p.m.

* The peak of this E.M.F. wave does not always occur quite in phase with the electromotive force due to the break. The actual magnitude of the rotational electromotive force will therefore be some proportion of the peak value, depending upon the position of the timing lever.

* Provided, however, as shown above, $L_2 q$ is kept large compared with R.

to help us in the right direction. Some further tests will be given in a later paper in which the direct effect of altering N_2 will be studied.

APPENDIX.

Some Tests of the Surface Dielectric Resistance of Leaky Plugs that have been in Use on an Engine.

In order to obtain some data as to the magnitude of the electrical leakage with spark plugs that have caused missfiring on engines, a series of such plugs were submitted to the following tests:—

(1) "Megger" insulation test (500 volts), cold.
(2) Test of leakage with voltages of about 10,000. Plug cold.
(3) A similar test with the plug at a temperature of 300° C.

The high-voltage tests were taken in a manner similar to that described on page 507. The magnet owas calibrated by finding the relation between the secondary voltage and leak. The plug was then connected to the magneto and the air pressure raised until it was just regularly sparking. The corresponding peak voltage was read, and from the calibration curve the equivalent conductance of the plug was read off.

The temperature tests were made with a pressure cylinder having an inside double tube heated by means of a specially constructed Bunsen burner. The temperature was ready by means of a calibrated thermo-junction.

The results of the tests are given in Table 6. The following points should be noticed:—

Table 6.

Spark Plug			Resistance of Plug					
				H.T. Test, Cold		H.T. Test at 300° C.		
No.	Make	Type	"Megger" Test Cold	Volts	Equivalent R	Volts	Equivalent R	Time of Run on Engine
			megohms		Megohms		Megohms	hours
1	Lodge	A	· 40	9,450	2·90	8,700	1·05	-
2	Rév	Porcelain	· 30	9,450	2·80	8,900	1·60	$17\frac{1}{4}$
3	Joly	B3	· 40	9,150	1·70	7,900	0·67	31
4	Lodge	A	· 40	9,450	2·9	8,700	1·05	57
5	Lodge	A	0·1	2,450	0·045	6,200	0·29	—
6	Lodge	A	· 40	8,600	1·00	8,400	0·90	$44\frac{1}{2}$
7	Lodge	A	· 40	8,450	0·93	8,500	0·95	$5\frac{3}{4}$
8	Lodge	A3	0·8	5,800	0·25	4,800	0·15	$49\frac{1}{2}$
9	Ponsot	Rotary air cooled	· 40	5,500	0·21	4,300	0·12	22
10	Rév	Porcelain	0·06	8,350	0·90	6,100	0·28	22
11	Jipe	No. 8	0·80	6,500	0·30	5,000	0·17	—
12	Oleo	27 G	0·03	2,000	0·03	1,200	0·017	$2\frac{1}{2}$

Spark Plug			Condition of Plug
No.	Make	Type	
1	Lodge	A	Dry carbon deposit
2	Rév	Porcelain	Clean surface
3	Joly	B3	Clean surface
4	Lodge	A	Clean surface
5	Lodge	A	Clean. Apparently sparking across insulation. Improved with heat
6	Lodge	A	Dry carbon deposit
7	Lodge	A	Dry carbon deposit
8	Lodge	A3	Very dirty and oily
9	Ponsot	Rotary air cooled	Dry and clean
10	Rév	Porcelain	Carbon deposit
11	Jipe	No. 8	Dry carbon deposit
12	Oleo	27 G	Very oily and dirty

(1) The "Megger" test gives a value of the insulation resistance which is much higher than the high-voltage test.

(2) The hot high-voltage test gives a value which is in most cases lower than that given by the cold test. There are two exceptions to this rule, viz. plugs Nos. 5 and 6. Inspection of the plugs showed that the effect of heat and high-tension current had been to burn away part of the carbon deposit, thus improving the insulation. For a normal carbonized plug, the insulation resistance at 300° C. is roughly about one-third to one-half what it is at atmospheric temperatures.

(3) Missfiring on an engine takes place when the plug insulation-resistance is somewhere between 10^4 and 10^5 ohms. In the above tests no attempt was made to keep the plug supplied with carbonized oil, etc., so that the insulation resistance would be higher than in the engine.

A large number of other plugs that had been used on engines for periods up to 24 hours and had not yet caused missfiring were tested, and in very few cases was the insulation resistance more than 1 megohm. The general deduction from the tests was that the average resistance of a sparking plug after a moderately long run was of the order of 200,000 ohms. Therefore, unless the ignition system can stand a leak of this magnitude, missfiring will take place very early in the life of the plug. The above result can only be taken as a general all-round estimate. It will depend upon the design of plug and the particular engine it is used on.

In conclusion the author desires to express his thanks to his assistants, Messrs. N. Ridgeway and R. McLeod, for considerable help in taking the observations.

EAST MIDLAND SUB-CENTRE: CHAIRMAN'S ADDRESS

By F. S. Grogan, Member.

(Abstract of Address delivered at Loughborough, *3 February*, 1920.)

In this Address I propose to draw upon my experience in life to touch briefly upon the electrical engineer, his training, work, and legal status.

The Engineer's Training.

A point I wish to emphasize is that the boy destined to become an engineer should be entered at the earliest date on the Science side of a school rather than on the Classics side. I submit that the early study of physics is a sure means to the improvement and development of the mental faculties. The education of the mind must be also more rapid than with classical studies.

The advantage of such a school training is that a boy is fitted to receive technical education at the various engineering colleges and universities. The successful student may generally after a three years' course at such a college obtain a diploma which becomes a valuable asset, more especially when the college selected is one in which professors are appointed not only upon their scientific attainments but on account of their practical knowledge.

Having secured a diploma the young engineer is now at the most difficult part of his career. He has the choice of remaining at college for research work or of seeking an appointment in either a works or engineering offices. With money both are easily obtained, but successful research work requires special ability. The difficulty in entering works is due to a want of co-operation between the engineering colleges and the manufacturing or municipal works. With such a training it should not be necessary to pay a premium to enter a works. A better plan is the payment of a small salary throughout a two years' pupilage, during which period the young engineer goes through the transition stage from student to engineer. I hope that one of the immediate results of the establishment of new Territorial Centres and Sub-Centres will be to attract into the Institution many Students at an earlier age, so that every Centre or Sub-Centre may have a Students' Section attached. One of the objects of those Sections should be to help the Students to obtain appointments.

There are many subjects which do not enter into a college course, and personally I do not think it desirable to add such subjects. I refer to book-keeping and ability to understand a balance sheet; Company Law and secretarial duties in connection therewith; works organization; sales organization for home and export trade, and general business methods. The trained engineer can easily acquire all the necessary knowledge of such subjects and many others should his work require him to have such knowledge.

I want to make it perfectly clear that the course advocated is that which in my view will be the most useful to those whose ultimate object is to become professional engineers. There are, of course, many subsidiary vocations associated with engineering works and offices where the training acquired in factory and office will be all that is required, but such positions are not necessarily filled by electrical engineers. The term "electrical engineer" is used by the public Press in altogether too broad a sense and should be limited. I will return to this subject when dealing with the engineer's status.

The Engineer's Work.

Let us consider for a moment the accepted definition of the engineer as one who "directs the sources of power in Nature for the use and convenience of man." With the same line of thought we may truly say that the electrical engineer "transforms the sources of power in Nature into electrical potential energy for conversion at his will into every other known form of energy for the use and convenience of man." He transmits that energy and converts it with the maximum efficiency.

The enormous scope of this work makes it imperative that directly an opportunity presents itself the young engineer should begin to specialize in one of the many branches. Whether he takes up manufacturing work or power-station work he will soon learn that there are again two divisions of each branch, the purely technical and the commercial. It is to be regretted that the remuneration of technical appointments is, on the whole, at too low a scale, but there are signs of improvement. Nevertheless it is a well-known fact that the technical man with commercial ability will readily command a higher salary. It is a good thing for the industry that all the larger engineering firms almost universally employ commercial representatives having a full technical knowledge. It is also most desirable that the manager of an electrical supply authority's undertaking should have not only the technical knowledge to run the works efficiently, but also a sound commerical experience to develop sales in his area for the use of electrical apparatus in our homes.

I am convinced that having secured a thorough knowledge of his subjects in any branch of electrical engineering the opportunity will present itself sooner or later to every engineer. The secret of success is to meet one's fellow-men, and this Sub-Centre should be such a meeting-place.

From such early work one emerges through many paths to the position of consulting engineer, professor at a university, Government, or public official, or director of a company. Whatever be the final position

occupied by each one of us, we must keep in mind that we are all members of one of the most important professions in the country. Each one of our personal problems must bear a close relationship with those of his fellow-members. It is essential for our mutual advancement that we should meet to exchange ideas, and the opening of this Sub-Centre will I am sure be welcomed heartily on every side.

To illustrate this relationship I could not give a better example than one taken from my own branch of the manufacture of domestic heating and cooking apparatus. From records taken over the last four years I have consumed electricity for lighting, heating, and cooking purposes to the extent of 4,400 units per annum. Now had I used electricity for lighting only the average consumption would have been but 200 units per annum. That is a net gain to the supply authority of 4,200 units sold to one house only. On this basis, and assuming that only a moderate proportion of lighting consumers were persuaded to adopt electric heating and cooking, the annual output of many power stations would be at least doubled.

It will be seen how the activity of the supply authority must help the manufacturer of domestic apparatus, and the latter helps the former by producing reliable apparatus. This activity in turn reacts upon all other manufacturers of power-station plant, cables and accessories. Further, in every case the load factor of the station would be considerably improved, resulting in the possibility of a cheaper supply. This again increases the possibility of further similar connections.

One already finds that the more progressive supply authorities are taking advantage of the clause in the new Electricity Supply Act giving power to such authorities to hire out apparatus to the public. From personal experience over many years I am convinced that by hiring out domestic apparatus in the first instance the confidence of the public is quickly secured and a rapidly increasing demand obtained, not only for hired apparatus, but for apparatus purchased outright.

To increase materially the home trade of any industry is also of great national importance, especially at the present time, for it enables manufacturers to secure a firm hold of export trade in colonial and foreign markets owing to improvement in works costs.

The Engineer's Status.

The prestige of the Institution was never greater than to-day; the Government have welcomed its assistance and advice on legislative matters. Also under its auspices manufacturing associations have been able to prevent adverse legislation which was about to retard our industry. Should we not therefore in the public interest and in our own require some legal status for the profession of the electrical engineer? Our sister Institution is promoting a Bill for the Registration of Civil Engineers. In my view it would have been better to have the single word "Engineer" in the title. The official designation authorized by the different institutions would still serve to indicate the branch of the profession to which an engineer is attached. Does this not lead to the suggestion of an amalgamation of our interests? The work of the Civil engineer, Electrical engineer and Mechanical engineer must be associated together in all large public works of the future, and now seems a suitable opportunity for the suggested amalgamation. Let us try it at this Sub-Centre. Having considered carefully the various aspects, I invite, in the name of the Committee, every engineer in our district, whether a member of the Institution or not, to attend our Ordinary Meetings.

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AUTOMATIC PROTECTIVE DEVICES FOR ALTERNATING-CURRENT SYSTEMS.

By A. E. McColl, Associate Member.

(*Paper received 12 February, and read before* The Institution, *29 April*, 1920.)

The purpose of the present paper is to deal with some recent developments in protective apparatus for alternating-current systems, and to describe a number of devices which have been omitted in recent papers on the subject.

The descriptive matter relating to a number of useful and interesting devices is available in scattered form in the technical Press and in various patent specifications. It is considered that these should, for comparative purposes, be available in more collective form and mark from time to time definite advances in the art.

Owing to rapid development in central station capacity, protective gear has now to deal with more severe conditions than heretofore. This has resulted in the development of a number of devices having different characteristics from the systems which have been in general favour for the last few years. Also, the increasing size of individual generating and transforming units calls for an increase in sensitiveness and a guarantee of stability not hitherto obtainable. Protective gear is essentially a form of insurance, and money judiciously expended in this direction may be considered a sound investment, as the expenditure entailed is usually only a small percentage of the capital outlay on the protected apparatus. This insurance is effective in a double sense, as individual circuits and apparatus are protected against complete destruction, and continuity of supply on the system generally is maintained.

Protective systems may be classed roughly under the following headings :—

(1) Leakage protective or core-balance devices either of the current, magnetic, or mechanically balanced types.
(2) Interlocked discriminating devices such as are applied to parallel feeder protection.
(3) Differential systems, the operation of which is based on a difference in quantity or direction of the current at each end or side of the protected circuit or apparatus.
(4) Special cable designs which by their construction partially or wholly function as protective devices.
(5) Reverse-power devices which operate when the power flows in the opposite direction to that normally intended.
(6) Simple overload devices which operate by excess current.

The foregoing is a rough classification of the protective devices to be described below.

Core Balance or Leakage Protective Systems.

Devices of this type are usually dependent for their inactive condition on a summing up of the currents in a circuit.

This summation may be obtained in several ways. A direct summation may be obtained by connecting the series transformers in star and the protective devices in shunt to the "starred" transformers. A balance may also be obtained magnetically. A third method may employ the currents so as to obtain a balance of forces by mechanical means.

Devices of this type form a simple, cheap, and efficient means of protecting many parts of a system.

Fig. 1 shows one form of core-balancing applicable to cases where three transformers on a polyphase system are available. With this method of connection the resultant current from two of the transformers is equal and opposite to that flowing in the third transformer. If the respective coils on the relay comprise an equal number of turns and are oppositely connected, it will be evident that magnetic balance will be secured. This balance will be disturbed only if current flows in

one phase which does not return by either of the other phases. Core-balance systems of the magnetic type cannot in themselves give protection against short-circuits between phases; but, where transformers on the

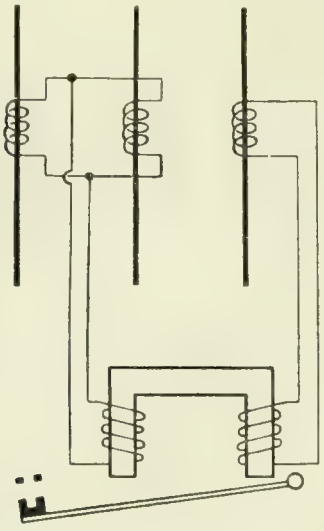


FIG. 1.—Magnetic balance relay as leakage protective device.

individual phases are available, ultimate protection can be given by the insertion of fuses in circuit with certain of the transformers.

This also applies to the arrangement just described.

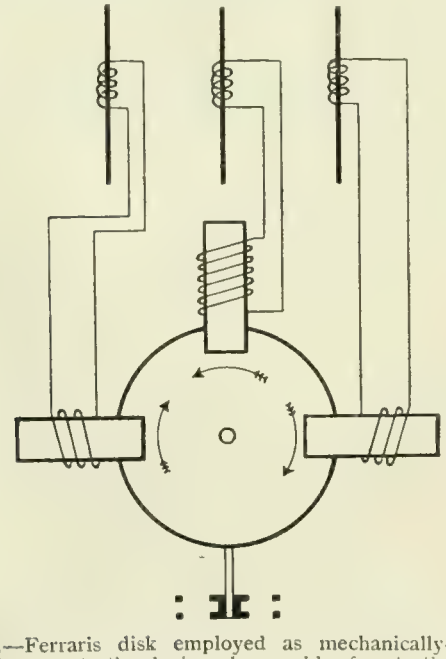


FIG. 2.—Ferraris disk employed as mechanically-balanced leakage protective device, also capable of protecting against unsymmetrical loading.

The insertion of fuses to give protection against the short-circuit condition introduces a time element in the operation of the protective device under conditions in which the most rapid operation of the device is required.

A solution of this problem has been attempted, employing mechanically instead of magnetically balanced protective devices.

One such solution due to the Allgemeine Elektricitäts Gesellschaft is shown in Fig. 2. This arrangement employs a Ferraris disk with three inducing magnets energized from the respective phases. Two of the magnets tend to rotate the disk in one direction. The third magnet is wound so as to give a torque equal to the combined torque of the other two magnets, but tending to cause rotation in the opposite direction.

If the phases are approximately balanced the resultant effect is a static condition for the relay. Earth faults on individual phases, and faults between any two phases, alter the ratio of the currents which give this static condition, with resulting operation of the device. Other arrangements involving a three-arm mechanically

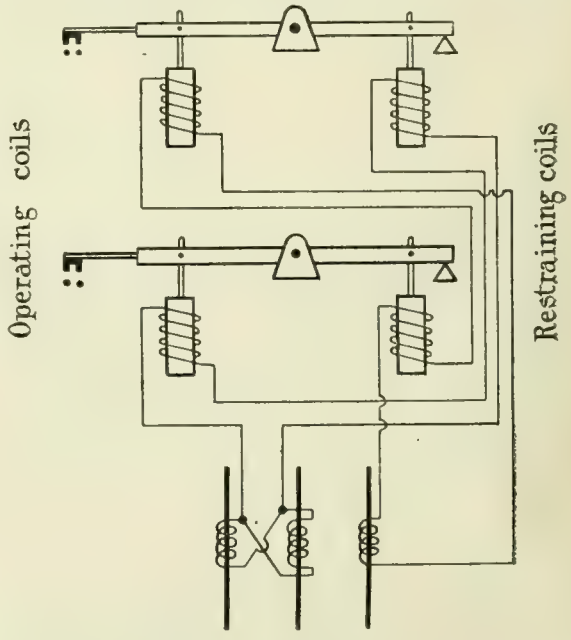


FIG. 3.—Biased leakage protective device which protects against unsymmetrical loading.

balanced relay have been proposed by Merz and Price giving similar protection.

With the various types of mechanically-balanced relays difficulty is experienced in maintaining a balance of the relay if a reasonably sensitive setting of the device is desired.

The generality of circuits on polyphase systems are not exactly balanced; consequently, to secure inaction of the relay under normal circumstances high fault-settings are required

A device intended to overcome this drawback is shown in Fig. 3. Instead of employing a direct balance in the mechanically balanced members, each member comprises an operating and a restraining coil. Two of the transformers are cross connected, and it will be observed that the operating coil of one relay and the restraining coil of the other relay are traversed by current which has a value 73 per cent in excess of that carried by the transformer on the third phase.

The mechanical forces are equalized, however, by winding the coils which are energized from the third transformer with 73 per cent additional turns. However, as a direct equalization of the forces is not desired, the distance from the fulcrum to the restraining coil is increased by, perhaps, 20 per cent over that accorded to the operating coil. We now have a biased leakage device which will not operate until the disturbance of the phase balance is exceeded by a definite percentage (20 per cent) either by leakages to earth on individual phases or faults between phases, increased stability being thereby obtained.

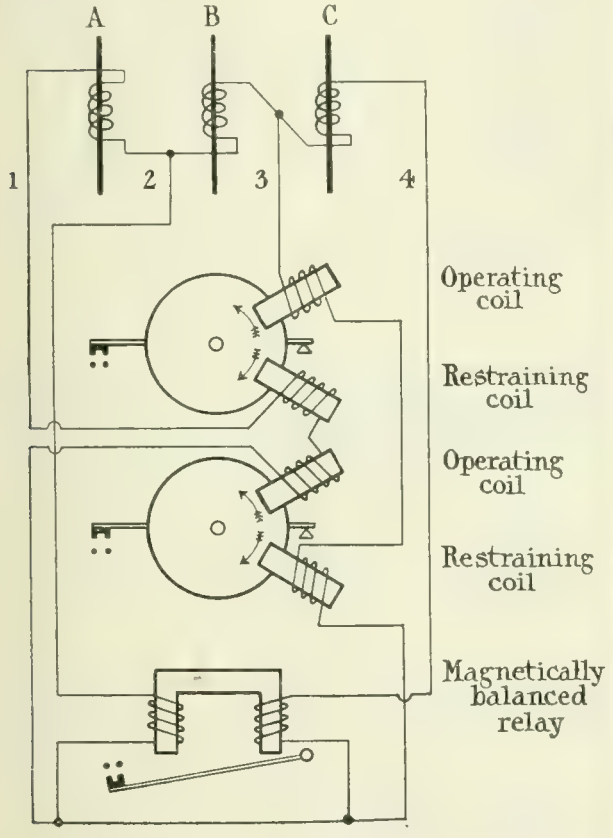


FIG. 4.—Combined arrangement for protecting against leakage and unsymmetrical loading.

Instead of employing the mechanically-biased beam device the arrangement may preferably operate with two Ferraris disks. By inserting a fuse in circuit with any transformer the arrangement will protect against ordinary overload.

A number of systems have the neutral point earthed through a comparatively high resistance, limiting the possible earth current on breakdown of a phase to moderate values. On such systems a device which is intended to protect against unsymmetrical loading, in addition to leakage current, requires to have a reasonably sensitive setting for earth faults.

Such an arrangement is shown in Fig. 4. This scheme provides for the employment of the biased-relay principle shown in Fig. 3 in conjunction with the leakage protective device described with reference to Fig. 1 to form one relay. Instead of plunger beam relays, biased Ferraris disks are shown. This combination admits of instantaneous protection being given with faults between phases or earth faults on individual phases. The relay setting for the first-mentioned condition of fault may be made without regard to the latter fault condition. That is to say, the mechanically biased portion of the relay may be biased to an extent sufficient to permit of reasonable unsymmetrical loading of the phases without operating the relay.

The magnetically balanced portion, however, may be set to operate with small leakage currents to earth on individual phases. The transformer arrangement shown in Fig. 4 permits of the employment of both relay types with one set of transformers. The current which flows in lead 2 is composed of the resultant current on A and B phases, and is equal in magnitude and opposite in phase to the current in the transformer on C leg and flowing in lead 4. It will be evident that the coils of the magnetically balanced relay may be connected in circuit with leads 2 and 4 and magnetic balance obtained.

The resultant current of the transformers on B and C phases flows in lead 3 and has a 73 per cent greater value than that flowing in lead 1. If the operating and restraining coils of the biased relay are connected in circuit with leads 1 and 3 the device operates in exactly similar manner to the arrangement described in Fig. 3.

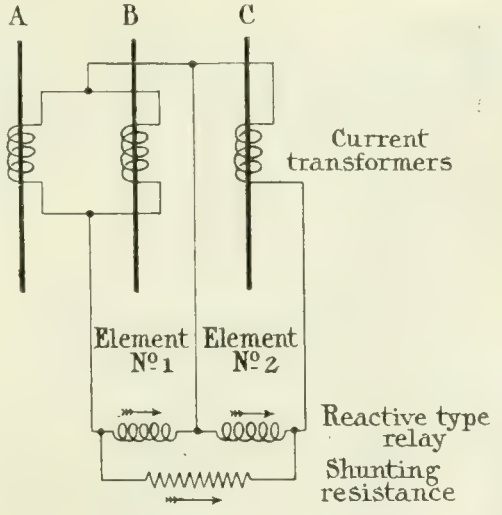


FIG. 5.—Reactive-type relay employed as biased leakage protective device.

A further application of the biased principle to core-balancing devices is shown in Fig. 5. With this transformer arrangement the equivalent of a simple circulating-current system is obtained. Normally, the circulating current flows straight through the two elements of the reactive type relay and the shunting resistance, the current direction being such that the relay remains biased. Should a fault to earth develop, say on C phase, the fault component of the current will flow along the equipotential lead and through the No. 2 element of the relay. As the fault current keeps increasing through this local circuit the main circulating current gradually

diminishes through element No. 1 and increases through the shunting resistance. Ultimately, the fault current reaches such a value that the whole of the main circulating current is forced out into the shunting resistance, and current flows in neither direction through element No. 1.

Further increase of fault current causes a portion to flow through No. 1 element in the reverse direction, thence through the shunting resistance, reversal of current flow through one element constituting the condition necessary for operating the relay. It will be observed that operation of the relay does not take place until all the main circulating current is forced out into the shunting resistance, this point determining the bias of the relay. The point at which reversal takes place through one element may be controlled by varying the ratio of the ohmic values of the relay elements and the shunting resistance. For example, if a 3 per cent bias is desired, the relative ohmic ratios of the shunting resistance and the relay elements would be of the order of 1 to 67.

Parallel Feeder Protection.

On the majority of power systems a favourite method of feeder lay-out consists in parallel or duplicate feeder supply.

This parallel distribution may be either by interconnection between distribution points or by direct radial supply from the generating centre. Protective means for such feeder arrangements commonly take the form of overload relays at the end adjacent to the source of supply and reverse power relays at the remote end. The function of the latter is to disconnect a faulty feeder by utilizing the reverse flow contributed by the healthy feeders in parallel.

An advance in the art of parallel feeder protection takes advantage of the principle that, normally, parallel feeders of the same length and cross section will share substantially in the distribution of the load current. A breakdown on one feeder, however, will alter the relative current values, so that usually the faulty feeder carries the heavier current.

A number of interesting and useful devices have been developed which take advantage of this condition. These devices are normally balanced against one another, but immediately operate to select the more heavily loaded of two or more parallel feeders.

In the future, as systems extend and existing installations are added to or duplicated, devices of this nature will find a larger field of application. The majority of interlocked relay devices operate on the balanced principle; a few systems have been developed, however, which employ the bias.

The biased principle as applied to parallel feeder protection was first proposed by Mr. Wedmore, and engineers generally have been slow to recognize the good features inherent in devices operating on this principle. With biased systems of protection, a definite measure of stability is obtained and smaller fault settings are thereby obtainable.

This particularly applies to the larger power schemes where the ratio of possible short-circuit current to the normal rating of the parallel feeders is large. With this condition small differences in balance become magnified and assume proportions sufficient to operate the protective gear of otherwise healthy feeders. If low fault settings are desired this unstable feature has to be tolerated, whereas, if an increase in stability is required, higher fault settings must be adopted.

Fig. 6 shows an arrangement of interlocked overload

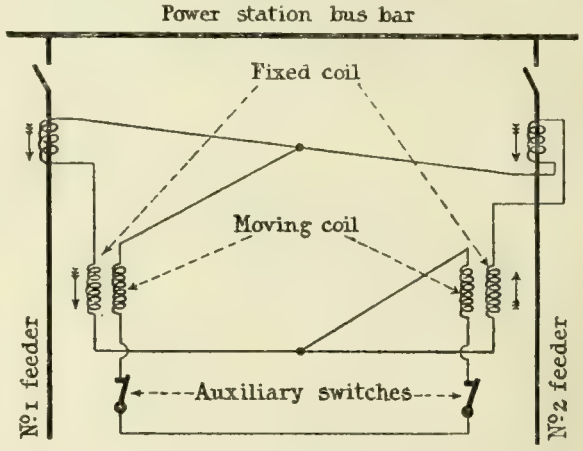


Fig. 6.—Parallel feeders protected by discriminating relays.

relays applied to the protection of two parallel feeders. The overload discriminating relays employed are of the reactive type, the fixed coils, say, being placed in series with the transformers which are connected for circulating current. The moving coils, however, are connected to equipotential points of the system. Normally,

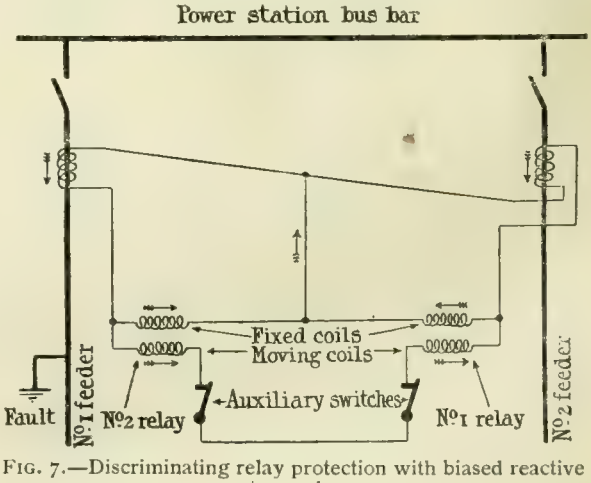


Fig. 7.—Discriminating relay protection with biased reactive type relays.

with balanced conditions on the feeders, no current traverses the moving coils of the relays.

The development of a fault, however, say on No. 1 feeder, will cause the difference current to flow through the moving coils. We therefore connect the relays so that when the excess current is contributed by the transformer on No. 1 feeder, the current direction is such that the relay of No. 2 feeder is restrained and that of No. 1 feeder operated.

If the excess current had appeared on No. 2 feeder, the relative direction of the difference current would have been reversed, with consequent operation of No. 2 relay and restraint of No. 1. This arrangement is capable of very sensitive settings, as the whole energy output of the transformers, that is to say load plus fault current, is employed to maintain the field of the relays. The employment of such energy, it will be observed, will make the relays immediately sensitive to small difference currents flowing through the moving coils.

The characteristic of the device will consist of increasing sensitiveness with increasing load. At full load with relays of robust design, the device is capable of operating with a $\frac{1}{2}$ per cent (1/200) difference current between the two parallel feeders.

As has already been stated, it is often not possible to utilize such extreme sensitiveness. If 1 per cent unbalance existed between the feeders, it is obvious that the $\frac{1}{2}$ per cent difference setting is not feasible, and if the feeders were subjected to 30 times their normal load current a 30 per cent setting becomes insufficient to ensure stability.

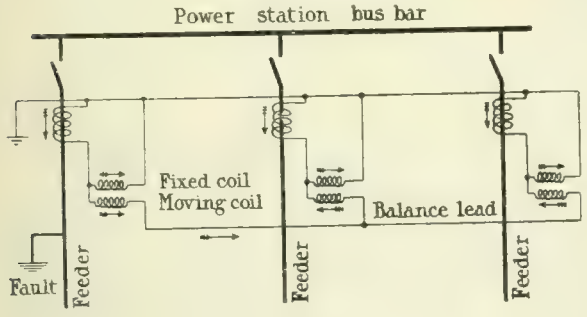


FIG. 8.—Discriminating relay protection with reactive-type relays.

A development of the arrangement just described in which substantially the same operating characteristics are obtained, but with the introduction of the bias, is shown in Fig. 7.

The transformers are connected for circulating current and normally the current flows straight through the parallel paths formed by the elements of the relays, the current direction being such that the relays are held in the off position. To permit of the description being more readily followed, the relays in the diagram are not shown beside their respective feeders.

Assume that a fault develops on No. 1 feeder. The increased current flowing in the transformer will circulate through the fixed coil of No. 2 relay and the equipotential lead. As the fault component of the current increases through this local circuit the load current which circulates through both transformers is forced to the outer circuit formed by the moving coils. At the same time, the current which flows straight through the fixed coil of No. 1 relay gradually diminishes.

A point is ultimately reached when all the load current is forced to the outer circuit and no current flows through the fixed coil of No. 1 relay. Any further increase of fault current flows by way of the outer circuit through the fixed coil of No. 1 relay in the reverse direction, thereby causing this relay to operate.

This device shows characteristics similar to that of the arrangement just described. That is to say, the feature of the load current being employed to maintain one element is likewise here obtained. The percentage bias is dependent on the ratio of the reactances of the fixed and moving coils; for example, with a 5 per cent bias these would have relative values of 40 and 1 respectively.

The ratio of the resistance or reactance of the fixed and moving coils being known, the bias is simply expressed by :—

$$\text{Percentage bias} = \frac{2\,B}{A} \times 100$$

where A equals the reactance of each fixed coil, and B the reactance of each moving coil.

The application of the directional relays to three or

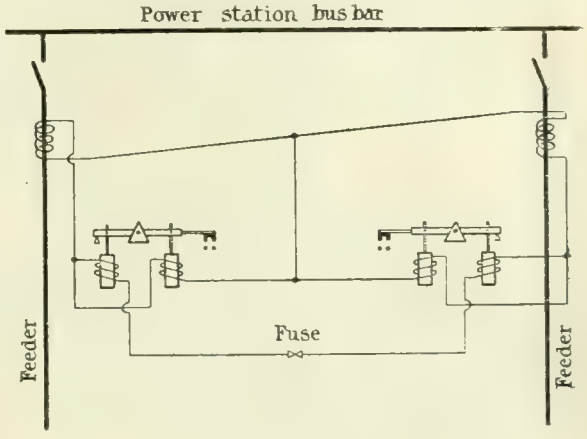


FIG. 9.—Parallel feeder protection.

more feeders with a parallel arrangement of transformers is shown in Fig. 8. Each transformer circulates its current through one element of its particular relay, the other element which is connected to the balance lead normally carrying no current. If the transformer on the faulty feeder carries the heaviest current the symmetrical loading of the arrangement is disturbed and the excess current spills through the element connected to the balance lead, operating this relay and restraining the others.

The substitution of the mechanically biased relay with a circuit arrangement similar to that shown in Fig. 7 is illustrated in Fig. 9. The transformer current normally circulates through the parallel paths formed by the operating and restraining coils of the relays. If one feeder carries current in excess of that carried by the other, the major portion of this excess flows through the local circuit formed by the operating coil of the relay protecting the faulty feeder and the balancing lead.

This particular arrangement may, by the insertion of a fuse in circuit with the restraining coils, be made to deal with sustained overloads on the parallel feeders. Such overloads might be caused by, say, a substation

busbar fault against which the interlocked relays remain ineffective.

It will be observed that the blowing of the fuse diverts the whole current through the operating coils, both relays thereby operating. When one feeder is disconnected it is necessary, in order to prevent operation of the relay of the remaining feeder, to short-circuit the operating and restraining coils of the relay protecting the disconnected feeder. This may be accomplished either by the relay itself or by auxiliary switches mounted on the feeder oil-break switch.

The extension of the principle of mechanically-balanced interlocked relays to parallel feeder groups exceeding two in number is shown in Fig. 10. Under normal conditions of current-balance on the feeders each transformer circulates its output through the operating and restraining coils of its particular relay. The balancing lead connecting points at equal potential on each relay circuit normally carries no current.

Disturbance of the balance immediately results in the more heavily loaded feeder sending a portion of its excess current along the balance lead. This current flows through the operating coil of the relay protecting the faulty feeder and distributes itself among the restraining coils of the relays protecting the healthy feeders. This current distribution is such that the relay protecting the faulty feeder is operated and the relays of the healthy feeders restrained. This arrangement is not necessarily confined to three but may be extended to any number of parallel feeders.

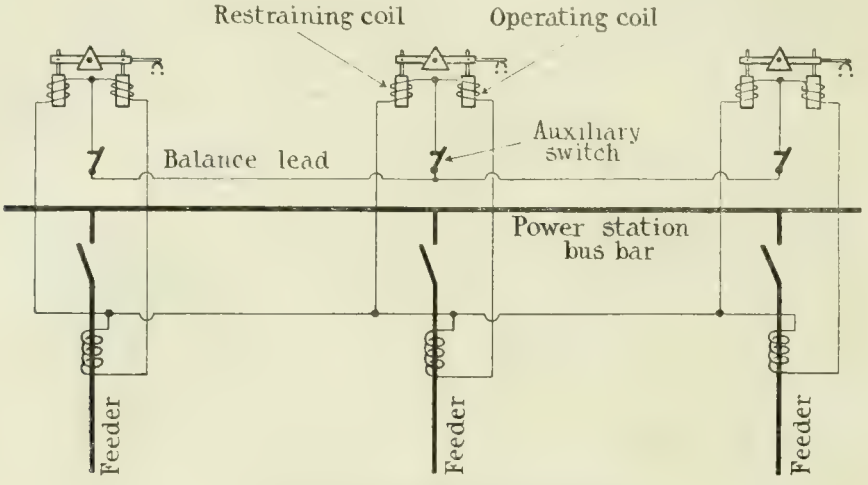


FIG. 10.—Parallel feeder protection.

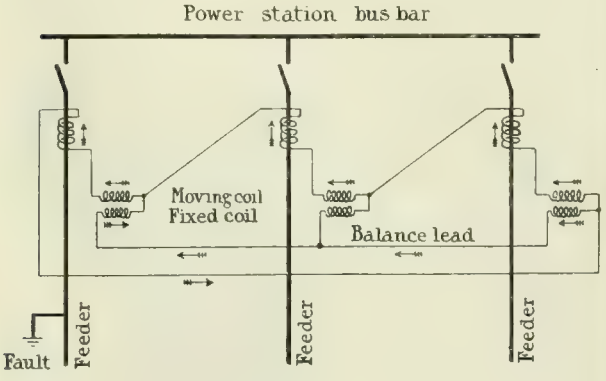


FIG. 11.—Discriminating relay protection with reactive-type relays.

Fig. 11 illustrates a further scheme of protection for parallel feeders by means of discriminating relays.

The relays in this case are of the reactive type, the moving coils, say, being connected in series with one another, and the whole arrangement including the series transformers being connected for circulating current. The fixed coils are connected to equipotential points by means of the balancing lead. On the assumption that the faulty feeder will carry a larger portion of the current than the healthy feeders, we arrange the polarity of the relays so that the overflow of current from the transformer on the faulty feeder will operate its particular relay and restrain the others. In this arrangement, likewise, the whole energy of the transformers is employed to maintain the excitation of the relays. The moving coils, consequently, will respond to very small current values which spill into the balancing lead.

Such an arrangement as that just described may be put on a percentage bias by winding a few turns on the field of the relay and connecting them in series with the circulating current system. This is shown in Fig. 12.

The relation of the few turns to the moving coil is such that the relay presses hard to the off position. The main field coil of the relay, however, is adjusted so that, if its particular transformer carries the larger current, it builds up a field in the opposite direction, which ultimately overpowers the restraining field and permits the relay to operate. A protective scheme of this description may have an unbalancing safety factor of, say, 5 per cent and operate at 1 per cent beyond this, i.e. 6 per cent difference current between the parallel feeders.

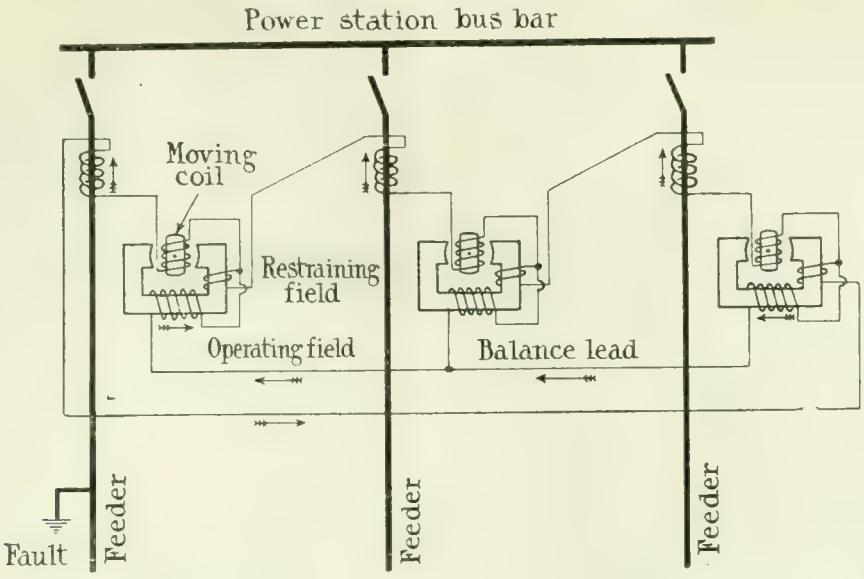


FIG. 12.—Discriminating relay protection with biased reactive-type relays.

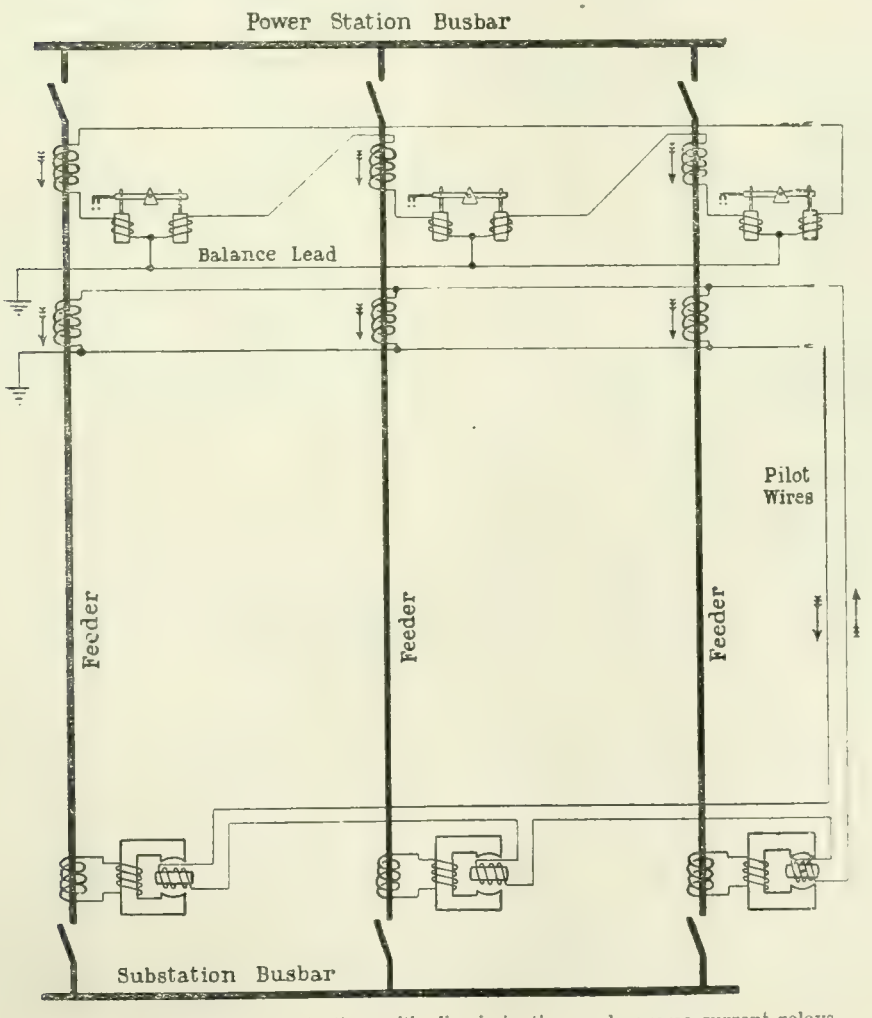


FIG. 13.—Parallel feeder protection with discriminating and reverse-current relays.

So far we have not dealt with the protection at the remote end of the parallel feeders. Generally this has been accomplished by means of reverse power relays at this end, any alteration of current direction in the relays being with reference to the potential of the circuit.

In the past a number of causes have contributed to unsatisfactory operation of the reverse power relay when associated with the end protection of parallel feeders. First, severe fault conditions between phases near the feeder end in most cases result in the potential being extinguished. Secondly, if the connection for the potential coil is taken from the star potential of the circuit, and the current in the potential and current coils is substantially in phase, we have a shift of 90 degrees in the phase of the potential coil.

This, of course, happens if the voltage triangle collapses on one side due to a short-circuit between two phases. There are consequently two conditions which make for non-operation of the relay under abnormal circumstances. These remarks apply only where the short-circuit current is of unity power factor. If the current at the fault point is lagging, there is a further shift in the relation of the potential and current coils.

A short-circuit between two phases may easily give rise to the condition in which a heavy forward current of low lagging power factor will operate reverse relays, and leave them inoperative with a heavy reverse current of similar power factor.

By connecting the reverse relays at the remote end for circulating current, an increase in stability has been obtained with heavy forward current of low power factor. This is possible provided the feeders retain their balance.

A connection which has recently been employed with a fair measure of success utilizes the current, say, in phase 1 and the delta potential across phases 2 and 3.

The respective vectors for current and potential are normally 90 degrees apart. These are pulled into their proper phase relation, in either the induction or reactive types of relay, by employing the requisite proportion of resistance or reactance in the potential winding. In the event of a short-circuit of magnitude sufficient to distort the voltage triangle, it will be found that the potential and current vectors retain their relative positions. Any further shift in phase relation due to low power factor at the fault point will not be sufficient to rotate the respective vectors beyond their proper operating quarters, although the relay may still remain unresponsive to the most severe conditions.

Fig. 13 shows a general scheme for the protection of parallel feeders wherein mechanically balanced relays are employed at the end adjacent to the source of supply and reverse relays at the remote end. The mechanically balanced discriminating relays, including their respective transformers, are all connected for circulating current.

Equipotential points on the various relays are connected together by a balancing lead. If the symmetrical loading of the loop is altered by one feeder becoming faulty, the transformer carrying the larger current diverts its excess current through the operating coil of its particular relay and by way of the balancing lead through the restraining coil of another relay. The impedance of the relay and transformer of the disconnected feeder may be cut out either by contacts mounted on the relay itself or by auxiliary switches operated by the feeder oil-break switch.

At the remote end of the feeders we have reverse-current relay protection but differing from that usually associated with this type of relay. Instead of being dependent on the potential of the circuit to give the determining action to the relay, a sample of current is taken from the parallel-connected series transformers at the source end by means of pilot wires. As consequent polarity will always be obtained in the relays at the remote end immaterial of the direction of current flow, the scheme is obviously unaffected by surges. The scheme has the further advantage that the heavier the fault the more definite is the action of the reverse relays.

When we come to deal with the protection of parallel interconnectors by means of discriminating relays the problem is more difficult. Each case has to be considered by itself. For instance, if a definite problem is taken, say four parallel interconnectors between two power stations, it is obvious that with a fault between phases we have a heavier current flowing into the faulty feeder at both ends than into the neighbouring ones. If the neutral point of the system is earthed through a limiting resistance this may no longer hold.

If the earthing resistance does not pass sufficient current, a leak to earth will cause the faulty feeder to open at one end and all the healthy ones at the other end. Should the neutral point be earthed at one station only, the problem is further complicated, and correct discrimination would only be obtained under all conditions either with the neutral point solidly earthed or with very low values of the earthing resistance. If this latter condition is fulfilled, the pilot wires may be dispensed with and the discriminating relay shown in Fig. 13 may be installed at each end of the interconnectors. Proper selection of the faulty feeder would now be obtained under all conditions.

In the case of a parallel group of four feeders to one substation the conditions are somewhat different.

Each end of the feeders may be equipped with discriminating relays, and correct selection would be obtained at the remote end for two feeders out of four. In the event of two feeders being cut out of circuit, there is no protection at the remote end for the remaining pair.

The logical development of parallel feeder protection in pairs is found in what is generally termed the " split conductor system." An extension of this principle, but with isolation of the conductors in the form of separate cables, has been extensively employed. The pairing of the cables in this manner often leads to difficulties in balancing, particularly on systems having a considerable plant capacity on the bars.

Although this unbalancing trouble is not much in evidence in split-conductor cables, it is often very marked where two cables are paired and protected as one unit. Paired feeders generally are not capable of such low

fault settings as the split-conductor cable, if it is intended that each retain a similar degree of stability. It is even questionable if paired feeders are capable of such fine settings as parallel feeders with interlocked relays for a similar degree of stability.

A distinct difference exists between the two methods of protection. Take, first, the parallel feeders. On each feeder we have a series transformer; and if under abnormal conditions current up to a value of 100 times the normal load of the cable flows, and 1 per cent difference in balance exists between the two cables, the resulting unbalance does not become 100 times 1 per cent, i.e. 100 per cent. The transformers may be designed to be saturated at, say, 20 times normal load, an unbalance of 20 per cent existing, and little further increase of secondary current is possible. A further increase of unbalance may result from the transformers themselves.

Secondly, with paired feeders a type of transformer surrounds the two cores which only carries the magnetic flux set up by the difference currents in the feeders. The flux, therefore, in this transformer is due to the 1 per cent unbalance existing between the cores. Under similar conditions saturation of this transformer is not

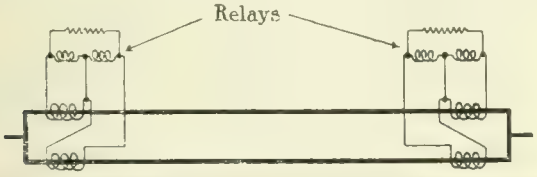


FIG. 14.—Twin cables protected by biased reactive-type relays.

possible; the degree of unbalance being progressive may reach the figure of 100 × 1 per cent, i.e. 100 per cent.

A scheme of biased protection for paired feeders employing the shunted reverse-current relay described with reference to Fig. 5 is shown diagrammatically in Fig. 14.

GENERATOR AND TRANSFORMER PROTECTION.

The more extended protection accorded to generating plant is a comparatively recent innovation. Opinion until recently was generally adverse to installing protective devices on generating plant. In certain cases such devices took the form of overload relays having delayed action, so that a generator could clear itself from heavy sustained faults on the distribution system or, by the joint action of a plurality of machines, from a short-circuit within its own windings.

An alternative protective means more extensively adopted consisted of the reverse power relay, this device operating with a reversal of flow into the faulty generator on a breakdown either between phases or between turns of the same phase.

In the past, protective gear on generating and transforming plant has been looked upon more from the point of view of preserving the continuity of supply than of saving the faulty plant from destruction. However, as power systems have grown in capacity and with them the output of individual units, it has come to be realized that it is not only essential to preserve the continuity of the service but also absolutely necessary to save the generating plant.

Generating and transforming plant is subject to three classes of fault conditions, these conditions comprising leakage to earth on individual phases, short-circuit between phases, and breakdown between turns of the same phase.

Generating plant is subject to further conditions such as accident to the prime mover and loss of field. The development of the differential system has permitted of the first two conditions being satisfactorily dealt with, and particularly where the neutral is earthed through a limiting resistance. The third condition can only be taken care of by the reverse power relay or some form of split winding.

The majority of fault conditions comprise those of the first mentioned class, consequently, the more satisfactory protection is given by the differential system. Furthermore, the reverse power relay demands a plurality of generating plant on the bars to give the reversed current or leading current of low power factor required by this device. The differential system does not require this latter condition as it may be set to operate while the current is still in the forward direction, and consequently with a minimum expenditure of energy at the fault point.

The differential system has the further advantage that it operates equally well with only one unit on the bars.

The necessity for the gear operating under this condition is to ensure the disconnection of the field circuit where this is dependent on the operation of the relay or the oil-break switch. The author considers that any form of protection is incomplete which does not embody this feature. Generators have been successfully disconnected from the busbars, but destroyed owing to the time interval elapsing before the excitation was removed. The circulating current system which has been described elsewhere is inherently a sensitive protective means. Full advantage may not be taken of this, however, owing to the general unstable tendency of the series transformers under severe emergency conditions. That is to say, where a generator protected by this system has to contribute its maximum instantaneous value of short-circuit current to faults on the distribution system there is a possibilty of the gear operating under this condition.

A number of causes may contribute to this unstable tendency. Chief among these, however, is the faulty choice of equipotential points and vector unbalancing. The possibility of the transformers developing different characteristics when the induction per square centimetre is pushed up to high values forms a further contributory cause.

When the maximum instantaneous value of the generator short-circuit current is known, the first mentioned cause of unbalancing is a calculable quantity and a definite setting of the relay based on this quantity is possible. The second and third causes of unbalancing are indefinite quantities and a high safe setting of the relay is necessary to ensure stability. This unstable

tendency has resulted in the adoption of higher fault settings, these averaging about 30 per cent.

With the large generating units of to-day, and the larger ones of the near future, a 30 per cent setting is too high. With a 30,000 kw. generator this setting might represent a very large amount of energy spent in continual destruction of the windings without operation of the relay. Generators may suffer from mechanical damage close up to the star-point end of the windings and ultimately break down to earth electrically, and, where the neutral point is earthed through a resistance, there may be insufficient potential above earth to permit of the necessary current passing to operate the 30 per cent relay setting. Destruction of the windings may here take place due to the heat caused by the prolonged arcing.

It should be borne in mind that the lower fault settings may mean all the difference between a lengthy

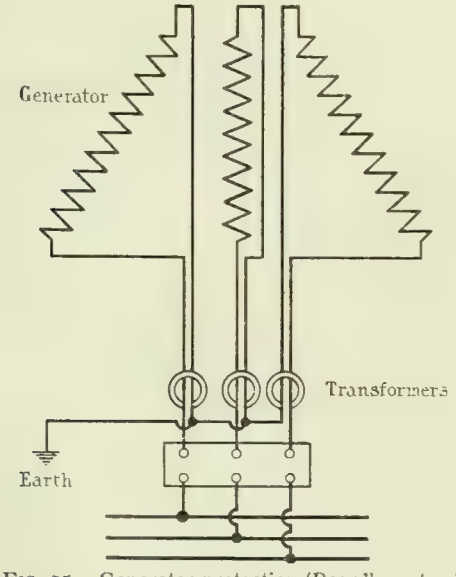


FIG. 15.—Generator protection (Beard's system).

and costly repair and merely a damaged coil which only requires the disablement of the unit for a comparatively short period.

Protective systems have recently been developed which have for their object a stability under severe emergency conditions and a possible fault setting not obtainable with the balanced current system.

One such system, due to Mr. J. R. Beard, is shown in Fig. 15. We have here a device which is unaffected by these unbalancing troubles, and the lowest possible fault settings may therefore be adopted.

In this system the input and output of each phase winding is directly compared and any resulting difference due to faults between phases or leakages to earth appears in the secondary of the core-balance transformer. This system may likewise be employed for transformer protection and readily lends itself for this application.

A development of the circulating-current system is shown in Fig. 16. To overcome the general unstable tendency of the circulating-current system under abnormal current flow biased relays are employed. This particular arrangement involves the employment of mechanically biased relays, one coil of which is traversed by the main current of the system, the other coil being connected to equipotential points. One such point, it will be observed, is midway along the restraining coil.

If a 10 per cent bias is desired it would be necessary to wind the restraining coil with approximately 10 per cent of the turns comprising the operating coil. It will be evident that the relay is held definitely in the off position until the unbalanced current flowing through the operating coil has a value equal to 10 per cent of the current traversing the restraining coil. The ampere-turns of the respective coils will balance one another at this value.

With such an arrangement it is possible to give a definite guarantee of stability, as ample latitude for unbalancing may be allowed. A suitable degree of bias for generator protection with this system would

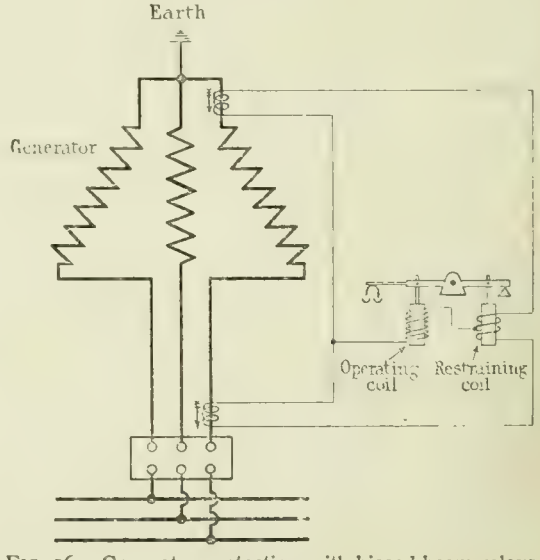


FIG. 16.—Generator protection with biased beam relays.

be about 5 per cent, and, with a relay designed to operate at 5 per cent beyond this, it would be possible to have a 10 per cent fault-setting with complete stability. If there is a reversed flow from the busbars into the generator fault, the operating coil carries the sum of the currents of the transformer at each end of the winding. This current divides and flows through each half of the restraining coil in opposite directions. The bias in this case is omitted, as this is a condition wherein it is not required.

Fig. 17 illustrates this system applied to a three-phase transformer bank having the star-star connection, two relays only being necessary.

A further development of biased protection is shown in Fig. 18. In this development a reactive-type relay is employed having its elements shunted by a resistance. The description of the arrangement shown in Fig. 5 applies similarly to this scheme. In this arrangement likewise a reversed flow from the busbars into the generator fault eliminates the percentage bias, as the

current flows in opposite directions through the respective elements of the relay. Fault settings comparable with those of the device shown in Figs. 16 and 17 may be obtained with this arrangement. Fig. 19 shows this scheme in connection with star-delta transformers.

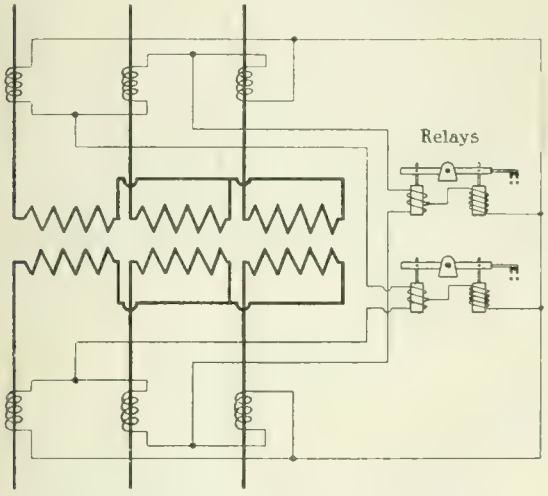


FIG. 17.—Star-star connected transformers and biased relays.

Another development of the circulating current system employs, instead of the balanced, an unbalanced principle.

It will readily be appreciated that while it is exceedingly difficult with the balanced current system to obtain

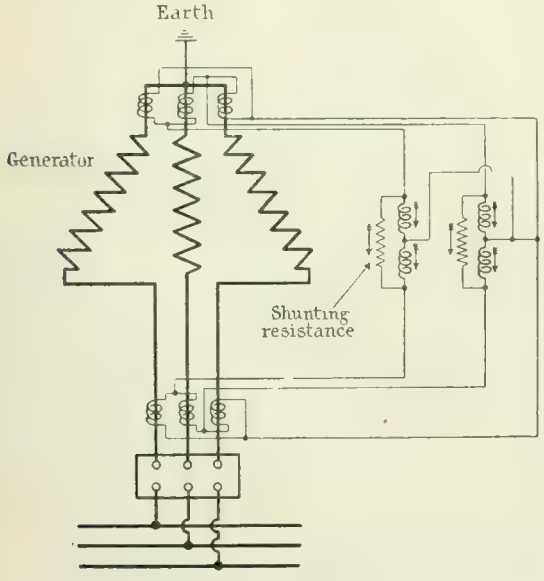


FIG. 18.—Generator protection with biased reactive-type relays.

a dead balance under varying conditions, it is quite a simple matter to secure a definite degree of unbalance. A scheme operating on this principle is shown in Fig. 20, the arrangement being shown on one phase only. The transformers are connected for circulating current and circulate their output through one element, say the fixed coil of a reactive-type relay, the moving coil being connected in shunt across the system.

Consideration of Fig. 20 will make it apparent that the fixed coil unbalances the circuit in favour of the transformer at the busbar end of the winding. Generally

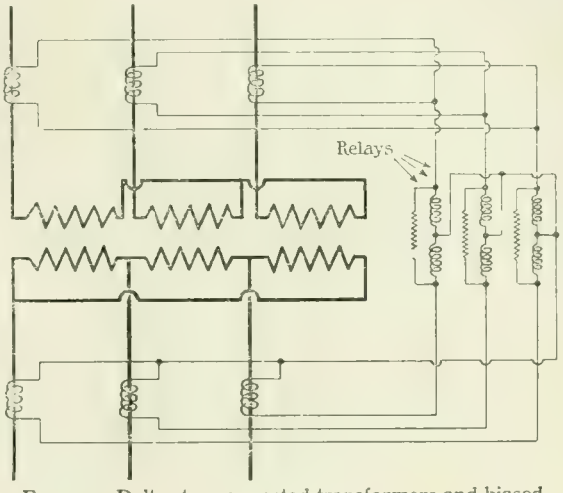


FIG. 19.—Delta-star connected transformers and biased reactive-type relays.

it will be found that in most wiring installations for the protective gear the greater lengths lie between the star-point transformers and the relay. This has the effect of unbalancing the circuit still further and increasing the percentage bias of the relay. Unbalance may

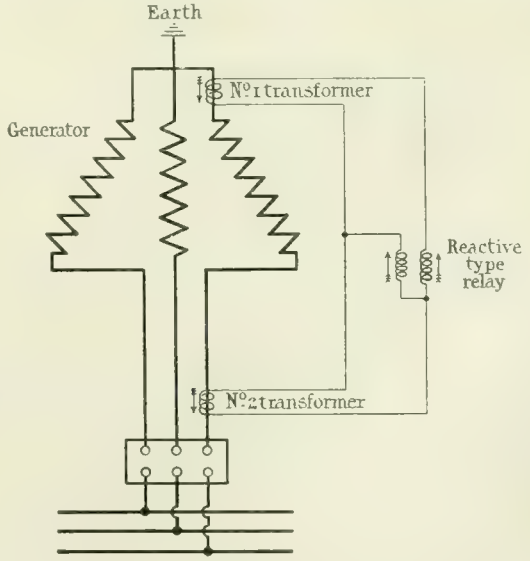


FIG. 20.—Generator protection with biased reactive-type relay.

also be obtained by inserting resistance in that side of the circuit, or by making the current capacity of transformer No. 2 slightly greater than that of transformer No. 1. The effect is to cause a small local current contributed by the No. 2 transformer to flow through the moving coil, the direction being such that the

relay is restrained under normal circumstances. If a fault develop to earth or between phases, there still being a normal delivery of power to the bars, the increasing fault component of the current in the No. 1 transformer will cause the small local current flowing through the moving coil to decrease. Further increase of fault current will cause a portion of No. 1 transformer's output to spill through the moving coil in the reverse direction, thence through the fixed coil, but in the same direction, as the load current circulating in the system. Reversal of flow through one element constitutes the condition necessary for operating the relay.

If the generator has to contribute abnormal current values to faults on the distribution system, the small local current which gives normal bias will increase and add to the stability of the relay. As already stated, unbalancing troubles with the balanced current system are to be feared only when abnormal current values have to be dealt with. It will readily be appreciated that it would be an advantage to run with a very small percentage bias at normal loads and automatically increase this percentage under severe emergency conditions. This may be accomplished by designing the transformers at the star point end of the windings so that they become saturated at a lower value of abnormal

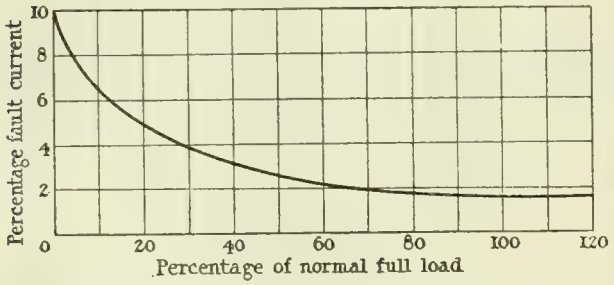


FIG. 21.—Curve showing fault current required to operate biased reactive-type relay with varying load current.

current than the transformers at the other end of the windings.

The effect is to cause the first mentioned transformers to fall off in ratio under these conditions much more readily than the busbar transformers. Increased current will therefore flow through the local circuit in a direction such that the percentage bias is increased. It is to be understood, however, that through the normal load ranges of the generator the transformers retain their relative ratios and characteristics.

With this arrangement the leakage and load currents are employed usefully in maintaining the field of the relay, the relay becoming immediately sensitive to small leakage currents flowing through the moving coil. Fig. 21 shows the general characteristics of the protection given by this scheme, increased sensitiveness being apparent with increasing load. It will be observed that at 70 per cent load and upwards the relay will operate with less than 2 per cent fault current.

The various arrangements shown in Figs. 15 to 20, while capable of dealing effectively with leakages to earth and faults between phases, are ineffective with a breakdown between turns of the same phase which does not develop into either of the preceding forms of fault. One solution of the problem of uniting in one relay a means of dealing with all the fault conditions, is shown in Fig. 22. In this arrangement the unbalanced circulating-current system described with reference to Fig. 20 is employed. The unbalance may be obtained either by inserting resistance in the circuit or, preferably, by increasing the current capacity of No. 2 transformer, a local current contributed by this transformer thereby flowing through the moving coil of the relay. This current, in relation to the flow in the fixed element energized from the potential of the system, gives the necessary bias.

With the development of leakage to earth or between phases, the increase in current in No. 1 transformer

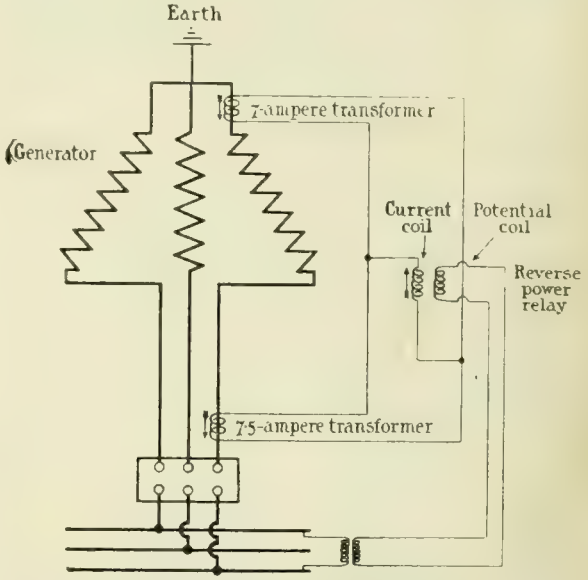


FIG. 22.—Generator protection with combined differential and reverse-current relay.

balances the circuit and ultimately spills through the moving coil in the reverse direction operating the relay, therefore, while normal delivery of power continues to the busbars.

A reversed flow into the windings due to, say, a breakdown between turns of the same phase will reverse the whole current in the circulating-current system and, likewise, the local current flowing through the moving coil which previously gave normal bias. The relay will therefore swing over to the operating side and disconnect the generator.

To permit of a better understanding of the scheme, it may perhaps be advisable to give an outline of the proportion employed in an actual installation.

The standard arrangement provides for No. 1 transformer having a full-load secondary current of 7 amperes. No. 2 transformer at the other end of the winding has a secondary current at full load of 7·5 amperes. The difference current of $\frac{1}{2}$ ampere normally circulates through the current element of the relay, the direction of this current relative to the potential of the circuit being such that the relay is held strongly in the off position. The current element is wound to carry

continuously this ½ ampere of unbalanced current, and the general proportions of the coil are such that the usual characteristics of the typical reverse-power relay are obtained.

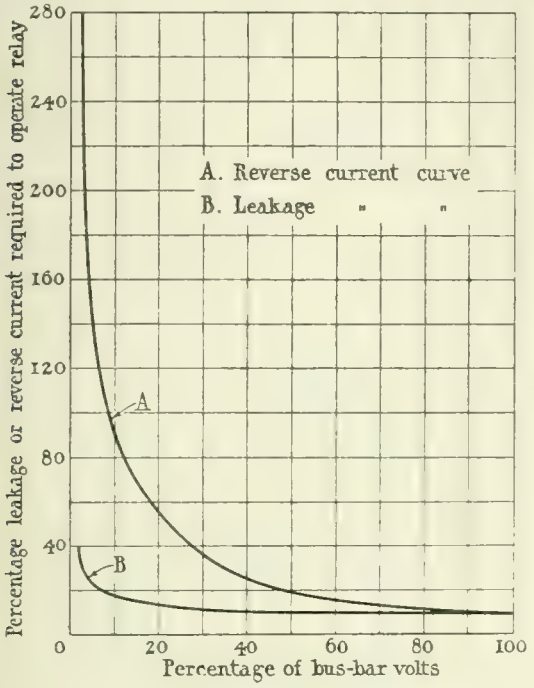


FIG. 23.—Operating characteristics of combined differential and reverse-current relay (without auxiliary coil).

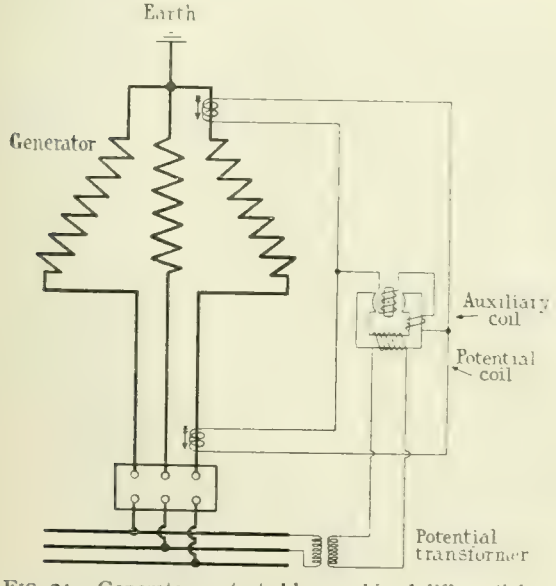


FIG. 24.—Generator protected by combined differential and reverse-current relay.

Now, if we have a reversed flow into the generator due to, say, an accident to the prime mover, the whole current in the circulating-current system reverses including the ½ ampere of unbalanced current which traverses the moving coil. The relay operates, therefore, in a manner similar to the usual arrangements of the reverse-current relay

Dealing with the other classes of fault which give rise to differential currents in the generator winding, a leak to earth or between phases will increase the current in No. 1 transformer. The effect, therefore, of this increase is to balance the relay circuit and finally to extinguish the ½ ampere of unbalanced current. To produce this result it is necessary for the fault current to reach a value sufficient to give 7·5 amperes in the secondary of No. 1 transformer. Obviously, the percentage fault current required will be $(0{\cdot}5/7)\times 100 = 7{\cdot}1$ per cent. Immediately the fault current exceeds 7·1 per cent, there is a reversed flow through the current element which brings the relay to the operating point.

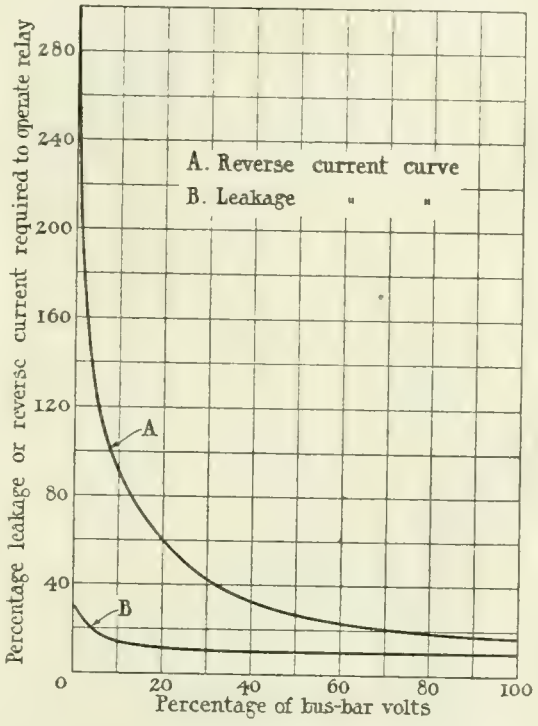


FIG. 25.—Operating characteristics of combined differential and reverse-current relay (with auxiliary coil).

Fig. 23 shows the characteristics of this scheme obtained with an induction-type relay.

Should better protection be desired on the differential side, it is necessary to install current transformers giving a larger secondary current. For example, if we employ transformers giving secondary full-load currents of 10 and 10·5 amperes respectively, the relay will operate on the differential side immediately the fault current exceeds 5 per cent. As the same value of unbalanced current is employed the reverse-current protection remains unaltered.

Objection is sometimes raised to the reverse current relay owing to the liability of the device to become inoperative with lowered potential. An addition to the previous scheme has been made which permits of the device operating if the fault condition is associated with low potentials. The appropriate means to secure

this result comprise an auxiliary winding consisting of a few turns wound on the same limb as the potential coil. In a relay of the reactive type this auxiliary coil is connected in series with the current element, the relation of the elements being such that the relay tends to operate.

Under normal healthy conditions the small field produced by the auxiliary coil is swamped by the preponderating field set up by the potential coil, and the relay is held in the off position. Fault conditions which cause a reversed flow through the current element likewise reverse the polarity of the auxiliary coil, the latter now aiding the potential coil. If the fault should be sufficiently severe to bring about collapse of the voltage, the auxiliary coil will now provide a weak field which determines the action of the relay. This scheme is shown in Fig. 24. Fig. 25 shows the characteristics of this device, in which it will be seen that operation at no volts is obtained on the differential side with 30 per cent leakage current. The curves in Figs. 23 and 25 refer to conditions in which the voltage and current are in phase. The function of the auxiliary coil is to ensure that the relay will not be rendered inoperative even under the most severe conditions.

The Differential System Applied to Feeder Protection.

Of the various systems operating on this principle the arrangements proposed by Merz and Price have been most extensively employed. As this system has been described elsewhere it is not proposed to recapitulate the details here. Developments and extensions of the principle will, however, be dealt with. All the various arrangements of the Merz-Price gear as applied to distribution systems have resolved themselves into one arrangement—the balanced voltage system. On the larger systems the limitations of the voltage balance method have long been realized. Current transformers having air gaps in the iron circuit have been necessary to ensure uniform characteristics between the transformers at each end of the protected lines, and also to keep the temperature of the transformer iron within reasonable limits.

With long feeder lengths capacity current in the pilot wires necessitates the adoption of higher fault settings, which consequently tend to place a limit, with the higher frequencies, on the length of feeder capable of protection with this system. The circulating-current system of Messrs. Harlow and Faye-Hansen with alternating-current trip reduces the capacity-current troubles to a negligible factor. Employing the leakage current direct, however, without the interposition of relays, raises the percentage protection given by this system.

The circulating-current system has, for the same transformer voltage, only half the capacity current in the pilot wires that is obtainable with the balanced voltage system. This will readily be understood as the balanced voltage system maintains a uniform potential between cores over the entire length of the pilot cable. With the circulating current system, however, the maximum potential between cores is obtained at the ends adjoining the transformers, a progressive decrease in potential being obtained until no potential difference exists between cores midway along the pilot cable. In certain of the arrangements shown, only 25 per cent of the capacity current possible with the balanced voltage system flows through the relays. The circulating-current system is more sensitive

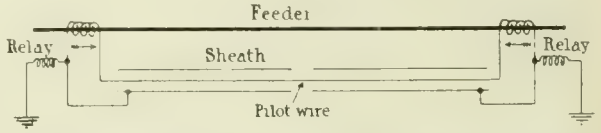


Fig. 26.—Sheathed pilot wire employed with balanced-voltage system to neutralize the effect of capacity current in pilot wire.

than the balanced voltage method, in that the leakage current requires to flow only through an alternative path connecting equipotential points, whereas with a voltage balance the leakage current has to be forced through the transformers at the remote end of the feeder in addition to the resistance of the pilot wires.

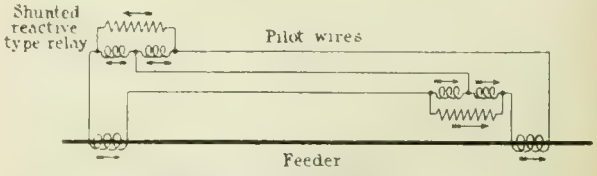


Fig. 27.—Circulating-current system and biased relays applied to feeder protection.

A recent development by Messrs. Hunter and Beard to overcome the capacity-current difficulty in the pilot wires with the balanced voltage system is shown in Fig. 26. In this development the capacity current which traverses each pilot wire returns by the metallic sheath with which each pilot core is surrounded. The relays, it will be observed, are unaffected by the capacity

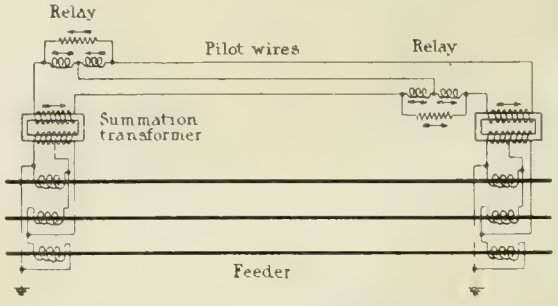


Fig. 28.—Three-phase feeder protected by circulating-current system and biased reactive-type relays.

current which flows in the local circuit formed by the metallic sheath and the pilot wires. A fault on the feeder, however, causes the transformers to send their current through one another and through the relays.

A development of the circulating-current system employing biased relays is shown diagrammatically in Fig. 27. This arrangement employs the shunted reverse relay described with reference to Figs. 5 and 18. Current

normally circulates over the pilot wires and through the elements of each relay and its shunting resistance, the relative flow in the elements being such that the relay remains restrained. If the input of the feeder exceed the output, the additional current forces the load current into the shunting resistance. A portion of the fault

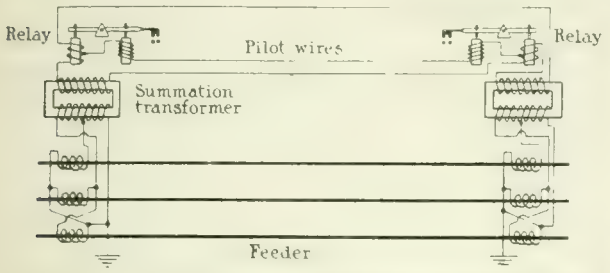


FIG. 29.—Three-phase feeder protected by circulating-current system and biased relays.

current traverses the shunting resistance and flows in one element of each relay in the reverse direction by way of the equipotential lead.

A fault fed from both ends is clearly a case where the percentage bias is not required; the relays therefore for this condition operate without the bias. With

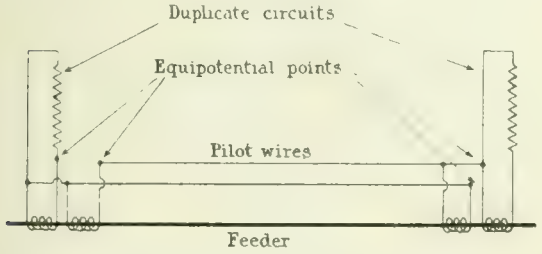


FIG. 30.—Circulating-current system applied to feeder protection with equipotential points obtainable at each end of pilot-wire system.

an arrangement such as this a 10 per cent bias may be employed, and, with a relay sufficiently sensitive to operate at 5 per cent beyond this value, a 15 per cent fault setting may be obtained. Capacity current in the pilot wires will not affect the stability of the relay, provided the ratio which such current bears to the load

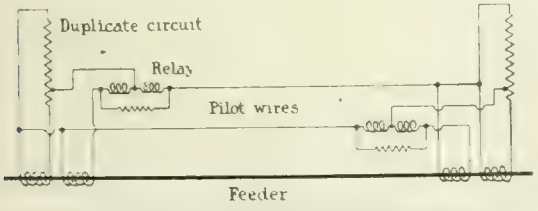


FIG. 31.—Feeder protected with biased relays.

current does not exceed the percentage bias. The application of the arrangement to a three-phase feeder is shown in Fig. 28. The primary of the summation transformer carries the sum of the currents of the phase transformers, the secondary delivering single-phase current to the pilot wires.

The employment of the summation transformer permits of the phase transformers being of normal design and of a ratio suitable for the usual 5-ampere indicating instruments. The necessary adjustment of the ratio required for the small pilot-wire currents may readily be effected by means of the summation transformer. The extension of the biased principle employing the mechanically biased type is shown in Fig. 29, the extent of the bias being dependent on the ratio which the turns of the operating and restraining coils bear to one another.

The circulating current system shown in Figs. 28 and 29 necessitates the employment of a neutral lead con-

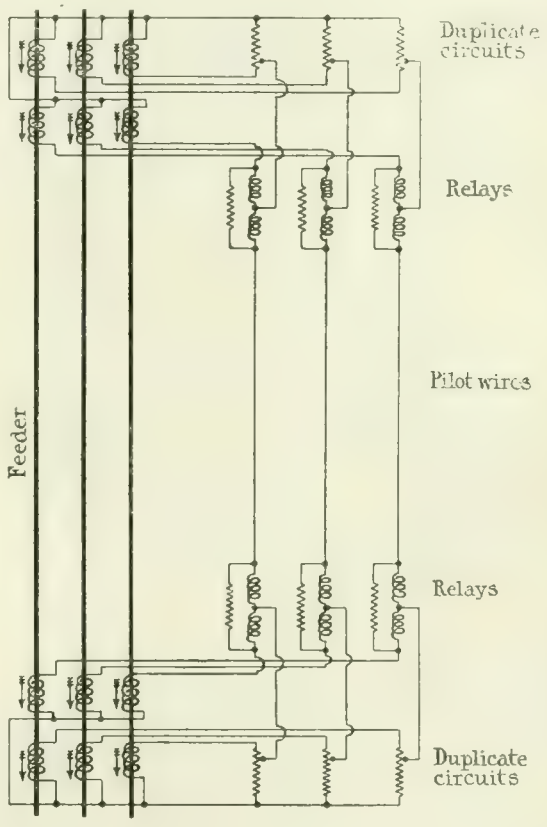


FIG. 32.—Three-phase feeder protected by circulating-current system and biased relays.

necting points at equal potential at each end of the pilot-wire system. Means whereby these equipotential points may be obtained without the balancing lead are shown in Fig. 30. It will be observed that if current is circulated over the pilot wires there is a continuous fall of potential until the transformer at the other end of the feeder is reached, the potential being raised again and a similar progressive decrease existing in the other pilot wire. Now we may duplicate this condition by creating a second circuit in parallel with the pilot wires. If this circuit have the same ohmic value, and similar current values are caused to flow through it, the conditions as regards fall of potential are duplicated. An infinite number of equipotential points will therefore

exist between the two parallel circuits. It is not strictly necessary for the duplicate and pilot-wire circuits to have similar ohmic values; these may, for example, be in the ratio of 1 to 10, the current values in the respective circuits being in the inverse ratio, a similar drop of potential, however, existing in each circuit.

Fig. 31 shows this arrangement of the circulating-current system in conjunction with the shunted reactive-type relay. Normally each half of the transformer secondary circulates current in its own particular circuit, the pilot-wire current of course flowing straight through the relay and its shunting resistance. A fault fed from one end causes the portion of the transformer feeding the pilot wire to send 50 per cent of its excess current into the duplicate circuit, such current dividing and flowing by way of the shunting resistance through each element of the relay in opposite directions.

It will be observed that breakage or destruction of the pilot wires causes the transformers at each end of the feeder to circulate their whole output into the duplicate circuits. Advantage may be taken of this feature to make the relays operate on overload by inserting fuses in the pilot wires. The adaption of this arrangement for the protection of a three-phase feeder is shown in Fig. 32.

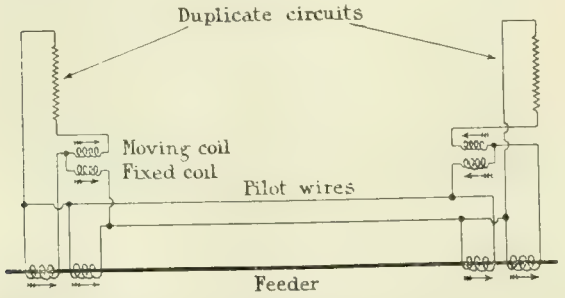


FIG. 33.—Feeder protected by circulating-current system and biased relays.

A further modification of the biased system which employs the reactive-type relay is shown in Fig. 33. One element, preferably the moving coil, is connected in series with the duplicate circuit, the fixed coil being connected between the duplicate and pilot-wire circuits. In this arrangement the bias is obtained by making the resistance of the duplicate circuits slightly greater than that of the pilot wires. The effect is to cause a small current to spill over from the duplicate circuits and flow through the fixed coil of each relay into the pilot-wire system, the direction of the spill-over current in relation to that flowing in the moving coil giving normal bias. If there be any difference between the input and output of the feeder, the transformer feeding the pilot-wire system at the more heavily loaded end sends a portion of its current through the fixed coil in the opposite direction, thence through the moving coil and the duplicate circuit.

It will be observed that not only the leakage current but also the load component of the current circulating in the duplicate circuit helps to maintain one element of the relay. That is to say, practically the whole energy output of the transformers is employed for operation of the relay.

With increasing load, additional energy will be available for operating the relay in case of a fault; consequently, the protective devices will, with increasing load, show up to a certain point an increase in sensitiveness.

As previously stated, unbalancing troubles are usually to be feared when the protected circuit has to carry momentarily abnormal current values. For normal conditions a comparatively small bias may be employed, and an automatic increase in bias obtained under the above-mentioned abnormal conditions.

This may be obtained by employing two transformers at each end of the feeder and designing the pilot-wire transformers so that they saturate at earlier values of excessive current than those feeding the duplicate circuits.

With the flow of abnormal current over the protected feeder the transformers which circulate their output over the pilot wires reach the saturated condition much earlier than those which feed into the duplicate circuits. The result is that the pilot-wire transformers, after a certain current value has been reached in the feeder, fail to give any further current, whereas the secondary current of the other transformers increases proportionately with the feeder current. Upset of the balance immediately ensues as the result of this condition. The transformers which circulate their output through the duplicate circuits attempt to restore this balance by causing more current to spill into the pilot wires. This current flows through the fixed coil of the relay in the direction which keeps the relay biased. The result is that still larger current values spill over from the duplicate to the pilot-wire circuits and increase the percentage bias.

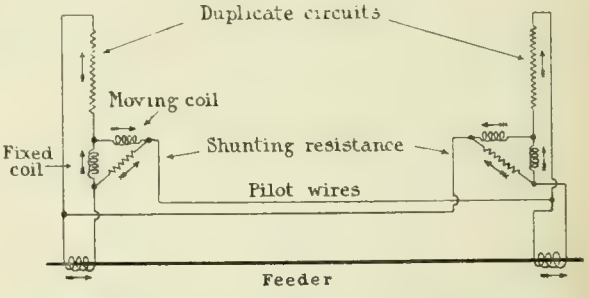


FIG. 34.—Feeder protected by circulating-current system and biased relays.

A modification of the preceding arrangement in which substantially the same operating characteristics are obtained is illustrated diagrammatically in Fig. 34. Instead of splitting the secondaries of the transformers, the resistances of the duplicate and pilot-wire circuits are adjusted so that half the transformer output flows in each circuit. If the shunting resistance has the same ohmic value as the fixed coil of the relay, it will be found that all the current flowing to the duplicate circuit traverses the fixed coil and the pilot-wire current flows in the shunting resistance. The moving coil will

therefore be connected across points at equal potential and will carry no current. To obtain the bias, however, it is necessary to make the ohmic value of the shunting resistance slightly greater than that of the fixed coil.

A portion of the pilot-wire current will therefore be forced through the fixed coil and spill into the pilot wires by way of the moving coil, the relative direction of this spill-over current being such that the relay is restrained.

Increased current appearing in one end of the feeder immediately causes a larger proportion of the transformer output to flow in the duplicate circuit, this increased current dividing between the shunting resistance

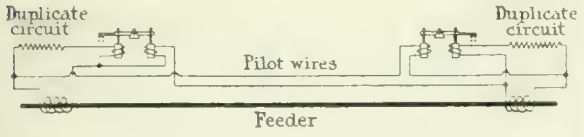


FIG. 35.—Feeder protected by lever biased relays and circulating-current system.

and the fixed coil, and the direction of the flow reversing in the moving coil.

The substitution of the mechanically biased relay with the same circuit arrangements is shown in Fig. 35. In this scheme also, in the single-phase application, the resistance of each duplicate circuit corresponds to that of one pilot wire. Under healthy conditions the output of each transformer distributes itself equally between the duplicate and pilot-wire circuits. The operating and restraining coils of each relay comprise a similar number of turns. The desired degree of stability is obtained by biasing the relay. This may be

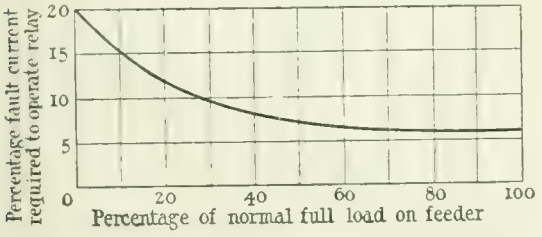


FIG. 36.—Curve showing percentage fault current required to operate relay with varying load current. Lever biased relay with 5 per cent true bias.

accomplished in a number of ways. The usual method provides for the leverage from the fulcrum to the restraining coil being increased by perhaps 10 per cent over that accorded to the operating coil. Alternative methods may consist in increasing the resistance of each duplicate circuit by, say, 10 per cent over the resistance of the corresponding pilot wire. The effect of this is to divert a larger share of the transformer output through the restraining coil of each relay. The same result may be obtained by adding the requisite number of additional turns to the restraining coils. In the case where a fault develops on a dead-ended cable, that is to say, where no reverse flow will ensue at the remote end, the fault component of the transformer current divides and flows through the operating and restraining coils in the ratio of 3 to 1. Should the feeding arrangements be such that a reverse current may flow from the remote end, the transformers oppose one another and divert their whole output into the duplicate circuits at each end of the feeder. This current, it will be observed, flows entirely in the operating coils of the relays.

Of the two circuits which each transformer supplies

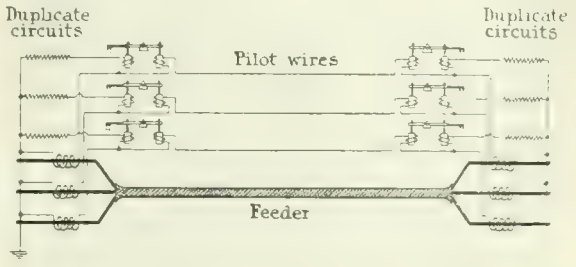


FIG. 37.—Circulating-current system with biased relays. Three-phase feeder.

it is apparent that only in one of these can capacity current flow. This refers to the pilot wires, the capacity current of which will traverse the restraining coil of each relay. Abnormal current flow, which may raise the potential of the series transformers to high values and give rise to considerable capacity current in the pilot wires, has no other effect than to increase the stability of the relay. Fig. 36 shows the operating characteristics of this scheme employing relays which have a mechanical or lever bias of 10 per cent or a true bias of 5 per cent. In a relay of the mechanically balanced type having open-circuit plunger-type coils the pull on the cores increases as the square of the ampere-turns. In this case the normal load current flowing

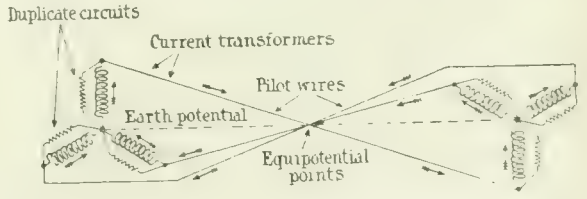


FIG. 38.—Vector diagram for three-phase circulating-current system, showing relation between pilot-wire potentials and potentials across duplicate circuits.

in the coils of the relay produces a high state of magnetization in the cores, the relay becoming immediately sensitive to the addition of a small amount of leakage current to the operating coil.

Fig. 37 indicates the manner in which the scheme would be applied to a three-phase feeder. With the three-phase feeder each duplicate circuit requires to have a resistance equal to half that of the corresponding pilot wire. The vector diagram for the three-phase circulating current system (Fig. 38) illustrates the relation between the resistance of the pilot wires and the duplicate circuits. It will be observed that the drop from either end to the midpoint of the pilot wires corresponds to the potential across one transformer.

Special Cable Designs.

A number of special cable designs have been developed which in themselves partially function as protective devices. These variously employ protecting shields round the individual or all of the cores, or leakage conductors embedded in the dielectric. In certain of these protective cables the inductive effects of the leakage current may be directly employed to trip the controlling switches without the interposition of relays

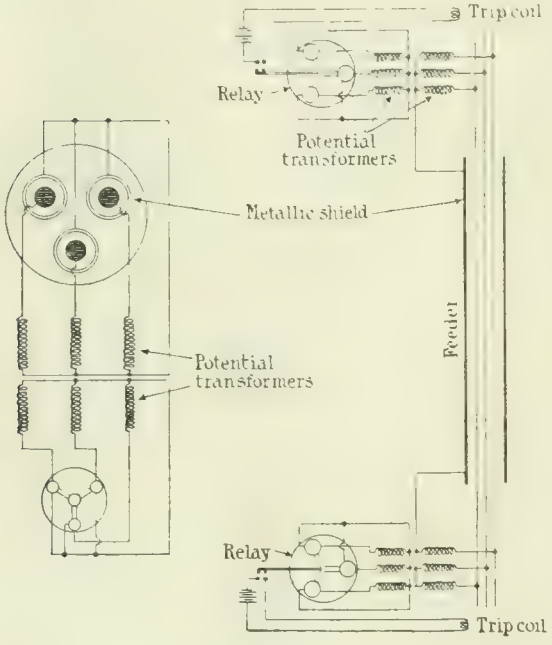


Fig. 39.—Bergmann protective cable.

or transformers. Such protective systems may therefore be designed to operate with comparatively small leakage currents.

A protective system employing a sheath surrounding each conductor is shown in Fig. 39. This arrangement due to the Bergmann Company employs potential transformers connected to the conductors and the surrounding metallic sheath. The secondaries of the transformers actuate a triangularly-spaced centrally-

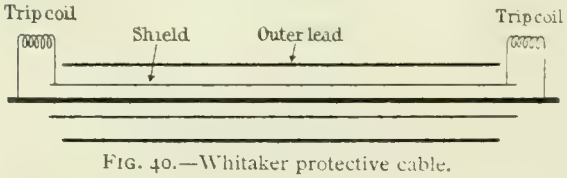


Fig. 40.—Whitaker protective cable.

pivoted three-arm relay of the balanced type, the balanced arm tilting over to either side according to which coil, on displacement of the floating neutral, develops the greatest pull. Alternatively, instead of the surrounding sheath the same system provides for a number of leakage conductors surrounding the cores.

Mr. Hochstadter has devised a protective cable which employs the sheath rather differently. This cable has the trip coil placed between each surrounding sheath and the lead covering. This scheme is really an extension of Waters's system to all the cores of the cable, with the advantage that faults between phases are also dealt with.

Mr. Whitaker's scheme which likewise employs the shield-surrounded core is illustrated in Fig. 40. The trip coil in this scheme is connected between the core and the shield and, consequently, has to be insulated for the full-line potential. In the author's opinion the shield is employed to better advantage than in the Hochstadter cable, as a greater thickness of dielectric exists between the outer lead and the shield. Extraneous influences, therefore, will not be so likely to nullify the protection should the outer or lead sheath be damaged

Earthing of the Neutral Point and its Relation to Protective Gear.

Earthing the neutral point is so related to the question of protective gear that it becomes difficult to consider each subject separately.

With low- and medium-pressure systems involving underground cables, present practice tends towards earthing the neutral point. This earthing may be accomplished through a wide range of resistance values, from the comparatively high ohmic values down to dead earthing, without any intervening resistance. The choice of the ohmic value for the earthing resistance will depend on the general extent of the individual system and on the fault settings of existing systems of automatic protective gear. With high-pressure transmission systems other considerations arise and the protective-gear question becomes of secondary importance.

Leakage protective or core-balance systems may be designed to operate with fault currents to earth which are small compared with the full-load rating of the circuit or apparatus which they protect. This applies particularly to the magnetic and current-balance systems and, in a lesser degree, to those of the mechanically balanced type.

Obviously, earthing resistances, having comparatively high ohmic values limiting the earth leakage current to moderate values, are suitable for this class of gear.

Parallel feeder protection by interlocked overload relays requires relatively large values of leakage current to give definite and correct operation to the protective devices, the ohmic value of the earthing resistance being governed by the current capacity of the parallel feeders. The leakage current necessary for operation of this class of apparatus requires to have a value substantially more than twice the full-load rating of the individual feeder. An example will illustrate the point.

Assume two parallel feeders, each carrying 200 amperes, and an earthing resistance capable of passing 400 amperes to earth. A leakage to earth on one feeder at the extreme end remote from the source of supply will cause 400 amperes of leakage current to flow in the faulty feeder and 400 amperes of load current in the sound circuit. This results in an inactive condition of the relays at the end adjacent to the source of supply. If the reverse relays at the remote end are connected for circulating current they will operate by change in relative quantity of the current in the feeders. If connected for straight

reversal, the relays at this end will likewise remain inoperative.

Disconnection of the faulty feeder at the remote end, however, still leaves the two feeders balanced. To permit the relays to discriminate correctly, it is obviously necessary to allow more than 400 amperes to flow to earth. If the earthing resistance were capable of passing, say, only 300 amperes, disconnection at the remote end would immediately result in the healthy feeder carrying the larger current, faulty disconnection following therefrom.

When the neutral point of a star-wound generator is earthed, the degree of protection afforded against leakages to earth is dependent on the ohmic value of the earthing resistance and the relay setting. Progressing along each phase winding towards the neutral point, we have a decreasing difference of potential to earth. Clearly, with a given relay setting and a certain value of the earthing resistance, a point is reached when insufficient current flows to operate the protective device. It is difficult to say at what minimum voltage a particular generator may break down to earth. The author has reason to believe, however, that breakdown corresponding to comparatively small potentials above earth has resulted from mishandling and mechanical damage. If it is intended that the relay should operate with faults which develop at a point corresponding to relatively low potentials, there is only one condition, i.e. to have the neutral point solidly earthed. This gives rise, however, to extremely large current values with earth faults on the distribution system. If again, the earth current is limited by the earthing resistance to moderate values, there is a point on the windings corresponding to a considerable pressure above earth, beyond which there is no protection possible. For instance, with a 6,600-volt 25,000-kw. three-phase generator protected by a device having a 30 per cent setting and its neutral point earthed through a resistance capable of passing 1,000 amperes to earth, such a point on the windings would correspond to 2,500 volts above earth.

If the fault on the winding were dead earthed, 1,640 kw. would be expended on the earthing resistance. Should the fault develop into an arcing earth the maximum energy expended destructively on the windings is represented by 414 kw. The fault might, however, originate at a point corresponding to the full potential above earth and, if the arcing condition is maintained, energy up to a maximum of 950 kw. may be released for destructive purposes without operation of the relay.

If the protective device is capable of a 5 per cent setting, the inoperative stage is reached at a potential corresponding to 420 volts above earth, or, with the fault "dead earthed," 46 kw. are expended on the earthing resistance. If from this stage the arcing earth develop, the maximum energy liberated for maintenance of the arc is only 11 kw.

Systems of protection depending for their action on the difference between the output and input of the protected circuit may be set to operate with leakage currents substantially less than the full load of the circuit, and particularly so with arrangements of the circulating current system. Systems involving special cable designs may be constructed to operate with small leakage currents; such arrangements might operate on unearthed systems where the earthed capacity current had a value of a few amperes.

The question occasionally arises as to whether the neutral point should be earthed through reactance or resistance. There is a natural tendency to consider favourably the use of reactance on the score of price and compactness. Full consideration should, however, be given to the possible effect of the reactance on the operation of reverse current devices where these are dependent on the potential of the system for their determining action. If the excitation for the reverse relays protecting the remote end of parallel feeders is taken from the star potential of the system, and the currents in the potential and current coils are substantially in phase, a fault on one phase to earth on either feeder with reactance in the neutral point may cause the current and potential vectors to assume positions 90 degrees apart. This will for the particular fault conditions result in non-operation of the relays.

Where the excitation is taken from the delta potential, and the current in the potential coil is in phase with its potential, the relative vectors might be displaced sufficiently to operate the relays of healthy feeders on forward current and leave the relay of the faulty feeder inoperative with reverse current. Various modifications of the connections involved and of the relative disposition of the current and potential vectors may be made which will lessen the tendency of the relay to operate incorrectly. The foregoing, however, is illustrative of the problems which must be taken into account when employing reactance in the neutral.

Discussion before The Institution, 29 April, 1920.

Dr. C. C. Garrard: The methods of protection described in this paper are based upon the biased principle, which was originally, I believe, developed by Mr. Wedmore, and we must give credit to him for his excellent pioneer work in that direction. The author's system is really a differential biased system. I have given considerable attention to it, and I am of the opinion that it will eventually replace, to a very large extent, many of the existing ones. If I may say so, the author is rather obsessed with a passion for thoroughness, and has described too many alternatives. We need not, however, be frightened. The essential features are the relays, of which there are three, and which are very simple. There is, firstly, the beam balanced relay, which is a very simple piece of apparatus illustrated in Fig. 35 on page 541, and the reverse relay shown in several of the diagrams. The beam balanced relay can be made a standard piece of apparatus easily adjustable, having the fulcrum so arranged that the bias can be altered to suit the circumstances of any case. I think it is very much better, wherever possible, to alter the bias mechanically than to use current transformers with varying windings. The

reverse relay is also very simple; and in addition there is a leakage protection relay which operates on the core-balance principle. A remarkable thing about these relays is that they do not require to be very delicate like ammeters or voltmeters. Some relays are used nowadays which are described as ultra-sensitive, which I am afraid rather frightens the engineers who use them. The author's relays are somewhat like ¼ h.p. motors, and are pieces of apparatus which a rough-handed switchboard attendant can adjust without disaster. I believe every station engineer will admit that this is a very great advantage, as is also the fact that standard-wound transformers can be used. That I think will appeal to many people. No accurate balancing of the transformers by the back-to-back method is necessary, and current transformers having complete iron cores without air-gaps can be used. Another point, as the author points out, is that capacity current in the pilot wire is positively an advantage because it increases the stability of the system. It should also be remembered that if a pilot wire breaks there is no false protection, because the cable is immediately disconnected. Moreover, standard oil switches can be used. For example, switches with split contacts are unnecessary. There is no doubt to my mind that protective systems like this, or the Merz-Price or the split conductor, are necessary nowadays for all large plants. It will be admitted, I think, that the earthed neutral will be the standard system in the future. An earthing resistance combined with an efficient protective system enables incipient faults to be disconnected. That is a state of affairs which cannot be reached by the ordinary methods of overload protection. Therefore every engineer who has to lay out a large power scheme must, of necessity, nowadays consider some form of leakage protection or protective gear such as I have enumerated. Coming now to the reverse relay, the complaint has been made with regard to many reverse relays that if the voltage disappears the relay is ineffective. I think the author clearly shows in his paper that with his instrument this is not so. The potential coil acts as a directive agency only, and, as we have a sample of current from each end of the winding of the machine, even if the voltage disappears altogether the protective gear still remains effective. If that is so, we have a tremendous advance over the ordinary reverse-power relay, which becomes ineffective if the voltage disappears on a dead short-circuit.

Major K. Edgcumbe: I think that this paper shows it is time the British Engineering Standards Association took up the question of defining the terms used in describing relays and other protective gear. For instance, the author uses the words "differential protection" (Fig. 24) and "discriminating protection" (Fig. 12) for practically the same idea. Again, I do not like his term "reactive relay" for what is usually called a "moving-coil" or "dynamometer" relay. The word "reactive" is too generally associated with "reactance." I was particularly anxious to see what arrangement the author would suggest for the protection of parallel feeders and interconnectors without the use of pilot wires or special conductors, but I regret to find that he puts forward absolutely none. He describes 12 or more different methods of protecting the power-station end of parallel feeders—which is not a very difficult problem—but I cannot find in the paper any scheme which can be used for the substation end, without the help of pilot wires. Fig. 14 does, I think, purport to protect parallel feeders without such, but when one comes to look into it one finds that it cuts out *both* feeders on the occurrence of a fault, thus doing away with any advantage as compared with plain overload protective. One serious objection to many of the proposals lies in the fact that accurate balance is called for between windings and resistances. For instance in Fig. 5, in order to get the correct bias, we are told that we must make the resistance of the shunt circuit 1/67th of the resistance of the relay coils. That may be easily done on paper or in the laboratory, but I do not see how it can be maintained under service conditions. Not only is there the contact resistance to be considered, but the coils are presumably wound with copper and therefore the question of temperature comes in. Again, I do not like the promiscuous use of fuses—for example in Fig. 9. It seems to me it is a retrograde step to introduce fuses in combination with relays. A relay is definite in its action and readily adjustable, whereas a fuse is at best a capricious piece of apparatus. In Fig. 9, moreover, it seems to me that they do away with all discriminating action, because with a number of these arrangements in series the fuses would all operate together in the event of a heavy short-circuit somewhere further out on the system. In a number of the author's schemes it seems to me that surges will disturb the bias, even if they do not actually cut out the wrong feeder. In Fig. 6, for instance, I think the sound feeder would be isolated in the event of a surge, and the faulty one would be left in circuit. The author brings forward several of the old and threadbare arguments against the reverse relay. I dealt with most of them in my recent paper,* and I hoped that Mr. Wedmore, in his contribution to the discussion, had given the quietus to the remainder. I am very pleased to find that the author emphasizes the advantages of giving a bias to relays. When I advocated it in my paper, not long ago, some speakers said that they did not like it on the grounds that if bias were required it must be a sign of weakness somewhere. I do not agree with that criticism. We do not want bias so long as everything goes on all right, but it is a protection against any accidental change in the resistance of the feeders or the ratio of the transformers. We might as well say that the safety valve of a boiler was a sign of weakness somewhere. So it is, no doubt. If everything is all right we do not need a safety valve, but that could hardly be regarded as a valid reason for omitting it.

Mr. J. R. Cowie: On old systems many of the devices described in the paper are extremely useful, and on large systems, where relays often operate when they should not do so, some of the devices suggested are being used successfully as stabilizers. On pages 528 to 530 of the paper these methods are explained, but it is when page 529 is reached that I become interested. In Fig. 11 it is assumed that the faulty feeder will carry the excess current, but if the fault is in the trifurcating box at the substation it appears to me that balance will be maintained and the relays fail to operate at the power station. It is from page 531 onwards that the author really deals

* *Journal I.E.E.*, 1920, vol. 58, p. 391.

with protection at each end of the line. Fig. 13 is good, but it uses pilot wires—as do the other suggestions from page 538 onwards—which mean capital expenditure. In any case I do not care about pilot wires, but modern tendency calls for them for telephones, signalling, also load-summation work. Perhaps the author will tell us what potential he expects to get on the pilot wires. I have been told that in some of his early arrangements this pressure was dangerously high. Now he is using circulating current. Will this arrangement disturb any telephone leads incorporated in the same cable? On page 532 in the second column the remarks on the protection of interconnectors are interesting. One wants to read this carefully, as at first sight the arguments appear wrong, but when gone into carefully the contentions put forward are sound. Finally, if we earth the neutral solid we get adequate protection. Earthing solidly is done, but instead of earth currents limited to 400 or 500 amperes we get values of four figures, and I have heard of 2,000 amperes going to earth at a fault. This seems to me wrong and an unnecessary strain on the plant. The logical development of parallel feeder protection in pairs is the split-conductor system. I cannot agree that difficulties arise on parallel feeders, i.e. two three-core feeders. When balancing, one knows the respective lengths and can assume that full potential is maintained at one end of the feeder. We then have the formula $\frac{L_1 - L_2}{L_1 + L_2} \times 100$ =percentage out-of-balance. We can then calculate the short-circuit current and get the out-of-balance under the worst conditions. I have feeders running with a difference of 22 amperes, and have successfully taken 30 amperes from one side of a line. With regard to generator protection, I agree that when the main switch operates, the field circuit should be automatically broken, as this minimizes fire risk. All the troubles one experiences in generator protection have been put forward—crippling of characteristic, shifting of equi-potential point, difficulty in finding that point, liability to change due to bad joints, coarse settings of relays, etc. The best method appears to be that shown in Fig. 15, but I should like to see the arrangement in Fig. 16 tried, because there is a wide field for the author's devices in generator protection. The systems described on pages 538 to 540 are useful and good, but all use pilot wires, which ought not to be adopted unless there is nothing else to be done. They cost a lot of money, and when they go wrong we may still believe the protective gear to be in commission, although it is not. I remember one case of a pilot cable going wrong. We could not find out what was wrong until we put a telephone on the line and then we could hear it. Ultimately we located it. The next case I remember was that of a pilot cable passing through very wet ground. We found when we were testing and ringing through the cable to see if everything was all right that the cable had broken down. The protective gear is now put through on another protective arrangement because of the great expense in renewing that pilot wire. For transformers arranged in groups the protection which I use is the circulating-current system, and that apparatus is sensitive enough to disconnect a transformer with a break in one primary winding. I remember a case of a transformer failing, and when we put a pressure test of 13,000 volts on, we could not find anything wrong. We switched it in and knew that there was still something wrong. The core was taken to the workshop, and we then found out by putting a heavy current through the winding and taking a drop test that one phase had a break in it. The gear is therefore very sensitive. The author and Major Edgcumbe say that we should use ordinary switches and compensate on the relays for series and potential transformer defects. Yes, if we can, but with the split conductor switch we only use one switch against two. Merz-Price gear starts by improving the transformer characteristic, but it does not go far enough, not even with the distributed air-gap transformers, and compensated pilot cables. The circulating capacity current is its trouble. Split-conductor gear is nearest to the ideal; this system uses special cables and switches, but the gear is difficult to handle when tee feeders come into the system. The special cables have, however, a high rating. Finality will, in my opinion, only be reached by tackling the problem at the series-transformer end, and I hope some day to use ordinary switches and ordinary cables with a new type of series transformer.

Mr. E. B. Wedmore: The kind remarks of the author and previous speakers disarm criticism. There are some five known types of relay, some 10 protective principles, and some 20 conditions of service, and if we ring the changes on these we can make a thousand diagrams. I feel that anyone who offers a paper of this kind should have full regard to the prior art, and in each case should show the reason why he prefers the particular arrangement that he has selected out of the thousand or more available, so that one may follow the advance of the art. In this paper we are offered a variety of devices for the same purpose, and the author has not distinguished between their relative merits and shown whether or not they represent a real advance. Some of the devices, too, are so lightly touched upon that it is impossible to discuss them. Such, for example, is Mr. Whitaker's protective system referred to in Fig. 40, a system quite distinctive and never yet fully ventilated. I agree with most of what Mr. Cowie has said. I think, however, that we shall hear a great deal more of Merz-Price protection in the future. The Merz-Price system was side-tracked by the introduction of the split-conductor system, which offered to solve all the difficulties of the Merz-Price. But the split-conductor system itself has its limitations. There are conditions which militate against it: for instance, where we have regulators in the feeders or where we wish to deal with step-up and step-down transformers in a line as one unit, and other features such as the use of a special switch. I believe the steps that are now being taken to overcome the well-known limitations of the early Merz-Price apparatus will lead to good results. A brief reference is made in the paper to Mr. Beard's proposals for overcoming capacity current in the pilot wire: I refer to Fig. 26. That system has been tried, but I do not think it will go very far, because of the high cost of the pilot wire. I believe the solution is more likely to be found on the lines of distinguishing between faults to earth and faults between phases in the protective apparatus. The reason why we want sensitiveness in the Merz-Price system is to deal with faults to earth. The reason why we want ability to stand tremendous short-

circuits is to deal with short-circuits between phases. If we differentiate between those two conditions we can at once greatly extend the range. We want a portion of the apparatus to be sensitive to faults to earth only, and this portion can readily be made insensitive to heavy short circuits. Then we want a portion to be operative on faults between phases only and with high settings. In this way we may extend the range of utility of the apparatus by 10 to 1 or more. I think the author has been the first to realize and incorporate in his devices the feature that, in applying a balanced system to generators, one should recognize that the unbalancing will always be in one direction. He utilizes this in obtaining a bias, and greater sensitiveness. I wish he had given us a little more in detail of the results he has obtained in practice. I think some of the arrangements shown will not live under service conditions. I should like to ask whether the generator protective system shown in Fig. 18 has been actually tested out and compared with that shown in Fig. 15. Even if the two systems gave equal test results, I would still favour Fig. 15, because it involves the use of apparatus which is of a more simple and robust character. One of the weaknesses which must be overcome is the multiplicity of parts. One is not predisposed to regard it as an advance in the art of obtaining reliability and stability when one finds that moving-coil relays have to be substituted for simple electromagnets, and relays with two or more coils and resistances and so forth; but if the apparatus is well designed and well tested out I am sure the author deserves to succeed with it.

Mr. H. W. Clothier: The idea of biased protection would have been a great comfort in the early days of experiment and development of Merz-Price protection when the avoidance of tripping of heavy "straight through" excess currents was one of the leading considerations. At that time the effect of capacity current in the pilot wire and the instability of current transformers working in voltage opposition were real difficulties. These, however, for the time were overcome by using transformers with a high straight-line characteristic. In order to obtain this, resistances in parallel with the primary or secondary coils were tried, but owing to the additional connections involved and the risks of deterioration and variation in the resistance, these were given up in favour of air-gap transformers. As the length of feeders increased, the effect of capacity current became more marked, and the margin between the fault tripping current and the safe "straight through" current became too fine, and split-conductor protection was introduced. Since then, however, it has been proved that by the use of a compensated pilot cable, mentioned by the author (Fig. 15), the unbalancing effect of capacity current is avoided by diverting the capacity current from the path of the relay. The air-gap transformers are now made in the multi-gap form practically independent of external interference, and having a straight-line characteristic up to 10,000 amperes. These would operate a robust electromagnet type of relay at a fault current of 500 amperes, or with the more sensitive Fawssett-Parry relay 160 amperes. This development resuscitates the original Merz-Price feeder balance protection, making it suitable for all lengths of cables and voltages of transmission, and gaining for it an advantage over split conductor, particularly in respect to economy on extra-high-tension feeders. The cost of the pilot wire may be reduced and the inconvenience of it disappears when it is possible to use the conductors in a complete cable together with the necessary telephone leads. In all these investigations importance was attached (1) to the use of relays and transformers of simple construction and with connections which could be plainly followed by any operative of ordinary intelligence; (2) to avoid the intervention of artificial resistances, capacity, or any devices which add to the number of independent parts and connections, any one of which, if defective, would tend either to render the gear inoperative or to cause premature operation; (3) to obtain a system of universal application, viz. for ring mains, occasional tees, parallel feeders, etc.

A considerable measure of success has been achieved, but, apparently, it is now suggested that there is scope for reform in respect to sensitiveness of fault setting. At present any tendency to trip on excess "straight through" currents can be counteracted by an increased margin on the fault setting, but I understand the alleged objection to obtaining stability in this way is that an excessive fault setting may be the cause of unnecessary damage to plant occasioned by the arc prior to the isolation of the fault. This change arises out of the further increase in the plant capacity which it is now the practice to install in generating stations. It is a matter requiring careful investigation. Plant has so far been safeguarded against excessive damage, not so much by reducing the fault setting to a minimum as by increasing to a maximum the speed at which the fault can be cleared from the system. The author does not state to what extent the devices he describes have been tried in practice. The unexpected frequently happens in protective gear work, and it is rarely safe to foresee faultless operation without extended practical trial. For instance, a magnetic balanced relay as shown diagrammatically in Fig. 1 was tried for Merz-Price current balancing, but failed as, owing to flux leakage, the separate limbs acted as independent magnets, and I would anticipate a similar result from any attempt to make a relay of this form into a magnetic balanced relay for leakage protection. The mechanical balance as in Fig. 3 seems more practicable, although in this case the poise of the rocking arm may be unstable at certain conditions of load, and, therefore, the relay may be susceptible to vibration. With regard to Fig. 4 is it not unusual to require protection against unsymmetrical loading? The arrangement of relay shown in Fig. 5 is a fundamental one appearing on feeder and generator protection in later parts of the paper. It requires to be seen in operation to be properly appreciated, but at sight of the diagram it would appear that the bulk of the energy from the transformers is absorbed by the shunting resistance, and, but for the statement of Dr. Garrard, I should have thought that the power left to operate the relay was such as to necessitate very delicate types. On page 539, a 10 per cent bias may be employed giving 15 per cent fault setting. This, compared with what has been done before with Merz-Price protection, is remarkably low. Will the

author give particulars of the volt-amperes required to operate the relays under such conditions and the maximum "straight through" primary current at which stability with these relays has been obtained? Referring to Fig. 26, the author shows the secondary of the protective system connected at both ends to earth. In an industrial district there would certainly be great risks of sufficient potential difference between the two earthed places at the respective ends to cause premature operation, and on this account it is the practice to earth at one end only. A system as shown on Fig. 29, using normal instrument current-transformers, would need to have bias to guard against the effect not only of capacity current, but also of the accumulated unbalancing of the several interconnected transformers, because each one will have a vectorial difference in voltage owing to irregularity in the permeability of otherwise identical iron cores, particularly at low flux densities and at and above the saturation point.

The author seems to favour Harlow and Faye-Hansen's suggestion of 1910 that current balancing was an improvement over voltage-balancing for feeder protection. It will be interesting to know the reason why this method has not matured. Something may have transpired on further investigation to show that the system of current balancing which was less attractive in practice than at first appeared on paper. Maybe it was found, except for very short lengths of cable, that the current balance did not actually reduce the capacity-current trouble so much as at first expected. Current balancing for feeders—at one time called "neutral wire balancing"—was tried on the North-East Coast. A test was made in 1907 on 13 miles of cable with transformers of straight-line characteristic and balanced to 6,000 amperes. The fault current to trip on an open-ended feeder was 400 amperes. The "straight through" current, before reaching the critical point of instability, was 3,000 amperes. A margin of 7·5 to 1. This was better than the margin on corresponding apparatus for voltage balance. But the "neutral wire balance" was not suitable for the protection of a feeder with a tee, as the variable load current through the tee made it impossible to fix definite equi-potential points. Whilst admitting that protection systems would be improved by the introduction of the bias which promises unlimited "straight through" current carrying, one must consider the disadvantages. Amongst these are obviously: (1) more complicated relay; (2) extra connections, and other parts. Whether there are operating objections which would appear in practice, such as the effects of magnetic inertia of relays when suddenly switching, or the instance of an internal fault occurring simultaneously with an external fault, remains to be proved by years of practical application or equivalent elaborate test before one can be so sure of it as of the existing known systems. With regard to generator and transformer protection, I do not think the author is quite right in saying that "opinion until recently was generally adverse to installing protective devices on generating plant." I know of 110 large generators protected by Merz-Price current balance since 1914. Other manufacturers could doubtless add to this number very materially.

The self-balance system shown in Fig. 5 is the simplest, and as it has also been proved to be effective in practice, it leaves very little room for improvement by the introduction of the additional parts and connections which would be required for the biased system as illustrated. The maximum "straight through" current which generator protection is required to withstand is the momentary maximum short-circuit current of one generator only. This is a limited amount which is definite and can be accurately dealt with, and there should be no difficulty in securing stability, given ordinary care in the design and manufacture of the current transformers and relays. For example, in a recent case a large modern generator having a full-load current of 2,250 amperes was fitted with gear giving instantaneous isolation at a fault current of 300 amperes, 13·3 per cent. This was designed to be stable up to 30,000 amperes "straight through" current. Taking a broad average, and giving due consideration to the tendency in the design of modern large generators to reduce the maximum short-circuit current per generator, there should be absolute security with self-balance protection at fault settings of 20 per cent of full-load current. This should be sufficiently low for all practical purposes, but if it were deemed necessary there is still scope for improvement in the construction of the relay which at present is the ordinary robust electromagnet type, somewhat similar to that used for common overload protection. This system is independent of the potential element altogether; that is, it depends entirely upon the current function. It is thus immune from the troublesome disturbances created by variations in pressure and phase displacement. The system shown in Fig. 16 of "current balance" protection with biased relays has also this latter advantage. It has, however, the disadvantage of a more intricate relay and connections, whereas the self-balance dispenses with the factors which created the need for the bias. The arrangement shown in Fig. 22, whilst providing for additional protection, viz. faults between turns by reversal of current, and also by reversal due to failure of the prime mover, has the disadvantage of introducing the potential element into the relay. The fault between turns has not nearly so serious an effect on the system as the fault between phases and to earth. Therefore, it is not so essential to cut it out instantly, and so it may be left for the short time which it requires to develop to earth, when it will be isolated so quickly as to avoid much further damage. The failing prime mover gives sufficient warning for hand isolation; moreover, it does not incur such risks of interruption of supply as to necessitate instantaneous removal. Any system depending for its operation upon the reversal of current must be fitted with an artificial time-lag in order to avoid premature and unnecessary operations on momentary reversals of current, such as may occur during synchronizing and other switching operations. It will be seen that those particular faults for which instantaneous release is not necessary, may be dealt with by a separate reverse-current protection with time-lag, but

these, if used at all, should be used only as an adjunct to some balanced system with instantaneous release. The system shown in Fig. 22, to be complete, must have instantaneous release for the faults between phases and to earth, and time limit to avoid premature operation on momentary reversals. The essential feature in restricting damage to generators, and this applies also to transformers, is the rapidity of the isolation of the fault between phases and to earth, and the simultaneous destroying of the main field. The rapidity of operation is of greater moment than highly sensitive fault settings. I agree with Major Edgcumbe's proposal to standardize nomenclature, but I would go farther and endeavour to standardize the requirements of users. The subject is so important as to warrant in the future a panel of expert users to give consideration to such proposals and, where necessary, to carry out research in the development of these new ideas. In the meantime I think this paper marks a distinct phase in the art of automatic protective gear.

Mr. H. Brazil: I should like to emphasize what has already been brought out by Major Edgcumbe and Mr. Clothier, namely, that there is more in this paper than we can readily assimilate, and the author does not give us the benefit of his experience by stating what he considers to be the best scheme for any particular purpose. One learns from bitter experience that, in actual working, conditions continually arise which were not, or possibly could not, be foreseen. Speaking from the supply engineer's point of view, one naturally wishes to know which of the schemes have been put into actual, practical use, and whether they have worked as satisfactorily as they would appear to do on paper. My feeling is that several of the schemes described aim at too fine a discrimination, and the author admits that, in order to prevent circuits being opened when they should not be, the sensitiveness of the relays has to be reduced. Coming now to the question of earthing resistances, I should like to suggest, first of all, that it is a mistake to call the current which flows to earth when a fault occurs (which current, according to Mr. Cowie, may reach 2,000 amperes) a leakage current; this term, I think, should be applied to currents of comparatively small value only, which do not, necessarily, themselves disturb the supply, and which may be on for hours, or days, or even continuously. The author states that if the ohmic value of the earthing resistance is too high, with certain kinds of faults, the current that passes to earth may not be sufficient to trip the automatic and cut out the faulty machine. The particular case that he refers to is where a fault occurs somewhere down the leg of a star-connected alternator, and although in my experience the great majority of faults occur on the first few coils, the case that he mentions may have to be dealt with. The author bases his statement on the assumption that an earthing resistance is employed which either has a fixed ohmic value or increases in ohmic value as it heats up. I should like to point out that if a resistance is installed having the opposite characteristic, namely, a negative temperature coefficient, the danger he mentions would, to a very large extent, disappear. Although the potential on the resistance may be considerably less than the star-voltage to earth, as it heats up the ohmic value decreases until eventually, if the fault remains on, the necessary current to trip the automatic is reached.

Mr. A. M. Taylor: I hope the author will say definitely in his reply which method of protection he considers to be the best for open-ended feeders, which for existing parallel trunk feeders that have not yet been protected by any of the split-conductor methods, which for the same conditions on new systems, which for interconnectors, and which for generators. There are one or two questions I should like to ask. For instance, where we have got trunk feeders protected from the generating stations to a substation on the split-conductor principle, and then from that substation onwards, either to another generating station or to another substation, we have got numerous existing feeders protected by the various older methods (i.e. without pilot wires or split conductors), what is the best method to adopt to protect some of these? In some cases that I know of, some of these feeders practically run as trunk circuits from the substation to another generating station. What can most easily be done to utilize these feeders and protect them successfully so that they will comply with modern requirements? Is it possible, for instance, to take a couple of three-phase feeders that run side by side and to balance them against one another on the split-conductor method? Is that being done, and if so where and with what success? I should also like to mention the question of faults between phases. As far as I know all the present methods of protection for clearing a fault between phases depend upon the principle that if the current leaks out of one phase and gets across to the other there must be somehow or other a fraction of current that leaks to earth at the same time, and therefore the core-balance effect comes in to give protection. If I am wrong, perhaps the author will put me right. Otherwise, I do not see how we can differentiate between a mere overload, or out-of-balance load current, and a fault between phases. As regards the fine setting of relays, I believe this to be the line we want to adopt. We want to get these balance arrangements introduced wherever possible, so that we can put quite substantial currents through our feeders to other parts of our systems, and can be sure that the relays will not come out unless there is something radically wrong in the particular section protected by them. In that connection it seems that the practice of putting overload relays in series with Merz-Price arrangements is rather a weakness, not only of the Merz-Price but of all forms of split conductors. I know of cases in which overload relays have been installed which would operate at a comparatively small current. What is the good of these split-conductor systems and of being able to pass a large current through them if they are going to operate owing to the overload relay at the end and yet are quite sound all the time? With a trunk system to the busbars of a substation and a large number of branches from that substation, surely it is better to have that trunk system at work at all costs, short of an actual breakdown on the busbars of the substation or on the trunk itself, than to have anything in the nature of an

overload relay in those trunks. Let the busbars and the feeders outgoing from the substation be protected with overload relays, but let the main trunks hold on. That seems to be the natural thing to do. To do otherwise is to suggest that the busbars cannot be protected as well as the feeders. Potential transformers on the busbars can be largely protected against pulling down the busbars by putting in three single-phase potential transformers in three separate fireproof compartments instead of one three-phase transformer. This improvement we introduced in Birmingham several years ago.

Mr. W. Wilson: I think the author's schemes possess two outstanding advantages. One of these is that quite ordinary apparatus is used—standard current transformers and simple and robust relays. In this connection I should like to acknowledge a weakness for the beam balance relay, which is especially simple in principle, construction, and adjustment. Secondly, there is the principle of what I may term a floating trip setting. We all know that 30 per cent of the capacity of a 50,000 kw. alternator is a very large amount of power to be let loose in destroying the windings; and by this expedient of permitting a small fault setting when the load is normal, and increasing it proportionately to any overload which may occur, the author has been able to reduce the fault setting to a very safe value. Again, the methods which the author has brought forward need no delicate adjustment. Major Edgcumbe referred to the 1 to 67 ratio specified on page 528, but as I read the paper, the question is not one of balance. The current divides itself between two paths, and if the stated proportion is observed, exactly the desired bias is secured. If, instead of 1 to 67, the ratio is 1 to 70 or 1 to 60, I take it that the bias will be slightly different from the 3 per cent contemplated, but that in all other respects the apparatus will go on as before. With regard to the numerous methods suggested, several speakers have raised the question as to which alternatives should be recommended, and I should like to state my own opinions. I particularly like Fig. 16 for protecting transformers and generators, when there is no objection to power flowing back into the apparatus. I think the advantages of simplicity are particularly evident in that figure, operating as it does by means of the beam balance form of relay. In Fig. 24 I was agreeably surprised by the completeness of the protection which one can obtain from this diagram. Being able to protect against faults in the excitation, and in the prime mover, as well as between turns of the same phase, is, I think, a step forward for which we should be grateful. For feeder protection, the scheme shown in Fig. 35 is again a beam balance system and is very simple and effective. The adjacent figure, Fig. 37, looks complicated, but that is merely because the author has made the diagram represent the protection of the complete three phases. With regard to Fig. 3, this shows a simple scheme upon the core-balance principle which should be very useful for protecting such apparatus as station auxiliaries. Here I should like to suggest a simplification. Instead of using two overlapping relays, it seems to me that good operation might be obtained by having a single relay with contacts at either end and two fulcra close together in the middle. Supposing the left-hand coil to suck down its plunger, the left-hand fulcrum would come into play and would give the desired bias; and the same holds good with regard to the right-hand fulcrum. Fig. A herewith shows the arrangement. This type of apparatus is as economical as could be desired, and deals effectively with the problem of the small discrepancies in balance which are unavoidable and unimportant. There is a brief criticism I should like to make with regard to the parallel feeder schemes. The author has stated that the faulty feeder usually carries the heavier current; as a matter of fact, a fault near the remote end would cause nearly equal fault currents in all the parallel lines. It seems to me that this drawback—that protection is not always secured—is rather a weak point of all the figures dealing with parallel feeder protection, except Fig. 13. Now the latter employs pilot wires, and is the only really complicated scheme in the paper. The suggestion I should like to make in this connection is, instead of using this special elaborate method for parallel feeders, that the scheme shown in Fig. 35 be applied to each of these three feeders and also to the three phases. At least three pilot wires are required

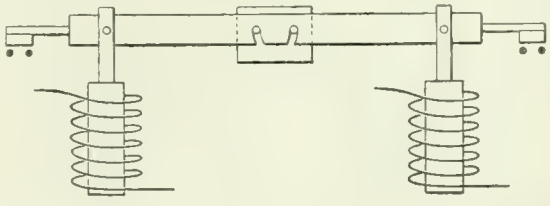


FIG. A.

for the former system, and only nine for the latter. We could then regard Fig. 35 as the standard for all classes of feeders. It would also do duty in the case of interconnectors, as it is a symmetrical system and will therefore act whether the current is flowing in one direction or the other. There would then be one standard system for all forms of feeders, interconnectors, parallel feeders and parallel interconnectors, free of complications in all cases. I take it that two pilot wires would not be required for each phase of Fig. 13; if that were so the arguments in favour of Fig. 35 would be still stronger. It seems to me that the relay shown in Fig. 24 has solved very effectively the troublesome problem of producing a reverse-power device which acts when the voltage has disappeared. It can quite easily be seen that when the potential coil is disconnected altogether the relay will act quite definitely, excited by the auxiliary coil only.

Mr. C. W. Marshall: Regarding the leakage devices which the author has described, the only scheme of any value at all seems to me to be the first one, but the author may be able to explain the advantages obtainable from some of the more complicated arrangements. Regarding parallel feeders, until some scheme is evolved whereby the space occupied by two separate switches can be reduced to that taken by a split-conductor switch I fear that undertakings with restricted room will usually use the split-conductor system. In comparing the balanced-voltage and circulating-current

systems, the author tells us that the latter system is superior to the former as regards sensitiveness. This is so for existing commercial designs, but if a more exhaustive examination of the problem is made it will show that there is no fundamental difference. With capacity compensation it is quite possible to get Merz-Price balanced-voltage gear with as good characteristics as circulating-current gear or even split-conductor gear. This involves the use of specially sensitive relays, and the author is probably aware of the fact that Messrs. Fawssett and Parry have such relays in commercial use. The author appears to consider it easy to get a definite degree of unbalancing, but I am of the opinion that it is quite as difficult to do this as to get exact balance. I agree with Major Edgcumbe that some of the terms used in the paper which are possibly meant to simplify matters, have not had that effect. The terms "reactive relay," "vector unbalancing"—which Mr. Clothier appears to be quite familiar with—and "current spilling" all seem to be rather objectionable. I hope that the author will be able to let us have the results in the near future of thorough tests on his apparatus. I think there is a possibility of a development on quite a different line, namely, from the metallurgical standpoint. Jensen is at present working on the properties of iron, and he has reduced the iron losses to a very small amount, and has some hopes of raising the saturation point of iron. When it is remembered that the problem of temperature coefficient was solved so successfully by the metallurgist, it is quite possible that the iron problem may also be solved.

Mr. A. F. W. Richards: The various devices described in the paper provide protection of electrical systems from shock in the event of cables breaking down, but none of these devices protect the feeders themselves. It appears to be assumed that cables must necessarily break down, and that all that can be done is to protect the system against the consequences of such breakdown. On page 542 certain special cables and apparatus for use therewith are described, but all the apparatus which is shown has the same effect. A form of cable especially designed by Mr. C. J. Beaver in 1912 and described in his paper of 1914,* detects initial incipient faults and thus provides protection for the feeders themselves. This cable has been adopted by (among others) the Admiralty at Portsmouth, and the Sheffield Corporation, and I believe I am right in saying that there are well over 100 miles of this type of cable in actual use. A copper tape is wound round the insulated cores and is itself insulated from the lead sheathing by paper dielectric, having about the thickness of a low-tension cable. Any incipient leakage from the core is detected by means of an electrostatic voltmeter placed between the copper tape and the lead. Insulation resistance tests are taken regularly between the copper tape and the lead, and these detect any damage to the sheath in the early stages before they eventually lead to the breakdown of the cable. I have actually taken a test on a cable which was running at 6,000 volts fully loaded and located the incipient fault whilst the cable was in commission, and repaired it at the week-end when it could be conveniently taken out of circuit. The feeder protection device, which has been adopted on a system in South Lancashire, is practically a combination of core balance and leakage protection. In the event of a cable fault, direct current is superimposed on the test sheath to actuate the trip, and the relays being polarized any induced alternating voltages in the sheath, which of course are unavoidable, are therefore negligible. But the chief feature of the cable is that since any incipient damage is anticipated, an actual breakdown of the cable is practically unknown. It seems to me that it is just as unpracticable to leave cables without periodical inspection, assume that they must break down and protect only against shock to the system, as it would be absolutely to neglect the boilers and simply protect the rest of the power house against consequential damage when one of the boilers blew up.

* *Journal I.E.E.*, 1915, vol. 53, p. 57

The President (Mr. R. T. Smith): With regard to the suggestion that the British Engineering Standards Association should set up a Committee to deal with the nomenclature of relays, the proper procedure is for the Institution to ask the Association to set up such a Committee with the object of preparing a Specification or Report, and if Major Edgcumbe, or Mr. Wedmore, or Mr. Clothier, or all three, will write to the Secretary of the Institution and suggest terms of reference to such a Committee, the Council will, I am sure, be very happy to forward them to the Association and ask that such a Committee be appointed.

Mr. E. T. Goslin (*communicated*): On a preliminary look through the paper, I was impressed by the bewildering variety of apparatus available for protecting power systems. The author has done his best in the paper to conceal the fact that he has a new scheme of protection, but the claims put forward that the differing characteristics of series transformers, and the effect of capacity currents in the pilot wires, need no longer be feared, will, if proven, be welcomed by all engineers concerned in the operation of alternating-current systems. On the system I am associated with we have had all the troubles and difficulties that the author mentions. Many "faults" have been caused or aggravated by the false operation of the protective gear. We, and no doubt many others, have long recognized the limitations of existing pilot-wire systems of protection. Whether our troubles are caused by capacity currents or the series-transformer characteristics, is a matter now being investigated. Possibly both contribute their share to the unstable features which have been mentioned. There is one contributing cause, however, on which I do not entertain any doubt, that is, in regard to the current induced in the pilot wires when these wires are strung on the same poles as the main transmission lines. Considerable trouble has been experienced on the gear protecting sections of our overhead lines, on the occurrence of abnormal current flow over healthy sections, and the tendency has been upwards in the matter of relay settings. Regarding the induced currents appearing in the pilot wires, it is figured that, with the spacing employed on our overhead lines, an unsymmetrical induced voltage of about 0·35 volt per mile may be expected at full load. With some of the equipment this will give suffi-

cient current to operate the balanced-voltage system with short-circuit current which is well within the capacity of our plant. The author claims for the system shown in Figs. 35 to 37 an immunity from capacity-current troubles; if this is the case an extended use of pilot-wire systems on long feeders is assured. I should like to ask the author how his suggested methods will withstand the induced current in the pilot wire which I have previously mentioned; this point is of considerable interest. On page 541 he refers to Fig. 36 and mentions "a lever bias of 10 per cent" and "a true bias of 5 per cent." This point is not clear to me. With regard to generator protection, I am in agreement with the author on the nasty results that happen when the circuits are not exactly balanced if the circulating-current system is employed. If biased relays are going to overcome our troubles in this direction, it certainly will be interesting to watch the development of apparatus along these lines. I am doubtful, however, whether fault settings as low as that shown in Fig. 21 are desirable for generator protection. I should like to know what degree of bias was employed to obtain the curve. An interesting scheme is shown in Fig. 22, which apparently combines the functions of the differential system and the ordinary reverse-power relay. Considerable controversy has raged over what is the best protection for generating plant. Some of the large manufacturing firms are not prepared to admit that the differential system meets the case. Others hold by the reverse current relay. It is known that certain fault conditions are best dealt with by the reverse-current relay, and others by the differential system. It is a pity that so little information can be obtained as to the proportion of faults most easily dealt with by each class of protection. The arrangement shown in Fig. 22 appears to tackle the fault either one way or the other. If it fails to do so on the differential side, it deals with it on the reverse-current protection.

Mr. A. E. McColl (*in reply, communicated*): I agree with Dr. Garrard that the beam balance relay is a simple piece of apparatus easily adjustable and possessing a robustness which is not a distinctive feature of many of the relays at present available. The bias may be easily varied by simply altering the position of the fulcrum, and this applies to any of the arrangements shown in the paper which employ the beam-type relay. The dynamometer relay, as Dr. Garrard mentions, may also be made a robust piece of apparatus partaking more of the characteristics of a small motor than of a switchboard instrument. Some of the designs with which I have experimented gave a pull of 8 oz. with normal full-load current through the current coil. This type of relay develops a tremendous torque under short-circuit conditions, and care must be exercised in the design so that this energy may be suitably absorbed without wrecking the relay. This can be most readily accomplished by designing on the lines Dr. Garrard has indicated. I agree that it is an advantage to be able to employ transformers of normal design which do not require to be balanced back to back. The earthed system will be more generally employed in the future and the great majority of faults will be disconnected in the initial stage. If we do not earth the neutral we are asking for trouble—in fact, we are going more than half way to meet it.

Major Edgcumbe objects to the terms I have employed in defining relays. I have used the term "differential protection" only where it relates to the input and output of a particular circuit and in this sense is applicable to feeders or generating and transforming plant. The term "discriminating protection" refers to the protection of parallel feeders and is the designation usually applied. Major Edcumbe is disappointed that I have put forward no new scheme for the protection of parallel feeders without pilot wires. I have not shown graphically any such scheme, but I would refer Major Edgcumbe to page 532 of the paper in which I say that "if certain conditions are fulfilled the balanced discriminating relay shown in Fig. 13 may be employed to protect both ends of parallel feeders without the necessity of pilot wires." Regarding Fig. 14, this refers to two separate cables which are connected as a split-conductor cable, and very naturally the relay will disconnect both cables as they are operating as one unit and would have one switch controlling the pair at either end. Surely Major Edgcumbe has not grasped the real meaning of the paper, of which the whole tenor has been to emphasize the fact that by employing bias the need for accurate balancing is done away with. Regarding Fig. 5 to which exception is taken, the bias of 3 per cent, which requires that the ohmic ratio of the shunting resistance be 1/67th of the resistance of the relay elements, is merely a ratio and does not require to be accurate. The ratio may be either more or less than this, the bias being merely a little greater or smaller according to the ratio and the relay operates similarly in either case. With reference to the question of surges cutting out the biased relays on parallel feeders, none of the arrangements in the paper should be so affected, as in the case of dynamometer relays both elements will be affected and the relative polarity of the relays will not be altered. I do not see that a surge should have any effect on the arrangement shown in Fig. 6, provided a balance is maintained on the parallel feeders. One element of each relay normally carries no current and the direction of current flow should make no difference to the stability of the relays. Major Edgcumbe admits the difficulty of obtaining balance between two good transformers. Obviously, the next step, if conditions will permit of it, is to install transformers which will give different characteristics to obtain the results at which I have aimed. The arguments against the reverse-power relay have been borne out by experience and, although I admit there is a field for this relay type on many systems, the arguments hold still more forcibly on the largest systems. One objection which I failed to mention in the paper is the large shift in phase between current and potential which would be obtained by the transformers becoming saturated on the flow of abnormal current. This shift is additional to that obtained by distortion of the voltage triangle on the occurrence of single-phase short-circuits and complicates the action of the relay under severe conditions.

In answer to Mr. Cowie I should state that the arrangements shown in Figs. 6 to 12 relate to the pro-

tection of parallel feeders at the source end. The protection at the remote end may consist of any of the usual arrangements of reverse-power relay and of which alternative arrangements have been described in recent papers on the subject. Alternatively, the reverse-current relay shown in Fig. 13 in conjunction with the pilot wires may be employed to protect the remote end. Regarding the voltage on the pilot wires, this depends on the length of the feeder to be protected. As an example, if ordinary designs of current transformers are employed with, say, 100-ohm pilot wires, the runaway voltage between pilot wires with star-connected current transformers and with maximum current flow would be from 1,500 to 2,500 volts. However, by suitably modifying the design of the transformers this voltage may be kept down to 200 to 250 volts per transformer as a maximum without introducing other undesirable features. Mr. Cowie does not agree regarding difficulties arising when running two separate cables as a split-conductor unit. Although the unbalance may be a very small percentage at normal loads, there is a considerable possibility of something radically different obtaining at, say, 50 times full load. Regarding the effect of circulating current on the telephone cores incorporated in the same cable as the pilot wires, I should not apprehend any difficulty, provided the telephone cores are properly paired throughout their entire length. At normal frequencies of 25 and 50 there should be very little trouble, if the transformers are worked at reasonably low flux densities so that the third harmonic may not be brought into prominence. Mr. Cowie doubts the value of the protection given by the arrangement shown in Fig. 11 if the fault develops in the trifurcating box at the substation. This is the most severe condition for parallel feeders protected by discriminating relays and likewise applies to the split-conductor system. In this case, of course, the faulty feeders at the substation end will either carry a reverse current or there will be a large difference current between the sound and faulty feeders, which will require the instant operation of the relay. Immediately the feeders are separated at the remote end the interlocked relays at the source end will discriminate and disconnect the faulty feeder.

I quite agree with Mr. Wedmore that the Merz-Price system has been somewhat side-tracked by the split-conductor system. I do not, however, quite follow the argument that improvements on Merz-Price gear are to be looked for along the lines of distinguishing between faults to earth and short-circuits between phases. I fail to see why the settings for faults between phases should be increased to enable the gear to stand up to heavy straight-through currents when the necessary stability can be obtained for the same condition with small fault settings. It is quite possible that if we ring the changes on all the known relay types, protective principles, and conditions of service, we can construct, not a thousand but ten thousand diagrams. Mr. Wedmore, however, should bear in mind that generally less than 1 per cent is available as commercial apparatus, and I have included in the paper a portion of the practicable devices. I do not claim that everything shown in the paper will appear as commercial apparatus, but it has been included nevertheless to illustrate some interesting features.

Mr. Clothier is quite correct in regard to a magnetic balance relay, wound according to the arrangement shown in Fig. 1, developing a large leakage flux which would operate the relay. In my early experiments this made itself evident, but by running on the two coils as a double winding exact balance is obtained. The diagram is merely representative of the principle on which the relay operates. Regarding the question of the necessity of protecting against unsymmetrical loading, a number of patents have been taken out by different people to deal with this condition. Presumably when one sits down to invent a new gear to take care of certain conditions the argument is that in all probability the experience has been such as to justify the new development. It seems to me that there are many cases of apparatus which have symmetrically loaded phases while everything is normal, but that the symmetrical loading is disturbed if the apparatus becomes faulty. Protective gear has been developed on these lines in America to take care of long-distance transmission. To what extent it has been used in practice I cannot say. Regarding the shunted relay shown in Fig. 5 and in several other arrangements, the current which flows through the shunting resistance is the load component; the component due to the fault must flow through the relay, and consequently this energy is available for operating the device. The volt-ampere output of each transformer in the arrangement shown in Figs. 35 and 37 is 46. A 10 per cent mechanical bias was employed, which, owing to the pull on the plungers of the relay increasing as a square law, resolves itself into a true bias of 5 per cent. The curve shown in Fig. 36 illustrates the characteristics of the relay. At full load on the feeder the relay operates with 6 per cent fault current or 1 per cent beyond the bias. The same relay tested with a 20 per cent lever bias or a 10 per cent true bias operates with 11 per cent fault current or 1 per cent above the bias. The curve refers to a pilot cable having a resistance per leg of 100 ohms. Feeder relays with 5 per cent bias have been tested up to 30 times full-load current on the primary side of the transformers without showing any tendency to operate. Generator protective gear according to Fig. 20 with bias of 1 per cent and fault setting of less than 2 per cent at full load has been tested up to 30 times full-load current with perfect stability. Fig. 26 is merely illustrative of principles, and the earth shown at each end of the pilot-wire system would not be adhered to in practice. I have no doubt that Mr. Clothier can point to instances in which generating plant has been protected for a considerable number of years, and I presume he refers to cases in this country where developments in the protective gear art are further advanced. My expression of opinion, however, has been in the broader sense, and reference to papers abroad will show that general recognition of the necessity for protecting generating plant does not date much further back than six years ago. Conversation with certain large Continental manufacturing concerns shows that

they are not prepared to consider any further advance on overload relays for the protection of large transforming units. I agree with Mr. Clothier that it should be possible to get low fault settings and complete stability on maximum straight-through currents with the self-balance system (Fig. 15). I should, however, have placed the possible fault settings at about half the figure he mentions. Whether Fig. 15 or Fig. 16 should be applied to a particular case will resolve itself into a financial proposition, as certain expenditure is entailed in connection with Fig. 15 apart from the protective gear, which is not necessary with Fig. 16. I certainly should prefer Fig. 16 for protecting transformer banks as it protects against breakdown between turns of the same phase, which is a common occurrence on the high-pressure side. With this condition, of course, Fig. 15 is unable to deal. I should apprehend difficulties in applying Fig. 15 to a 100,000-volt high-tension delta-connected transformer bank, and I should like to know if Mr. Clothier is prepared to bring two cables with 100,000-volt pressure difference through one transformer ring. Regarding the addition of time-delaying devices to generator reverse relays, this was a necessity in the days of reciprocating engines with drop valve gear when violent hunting was caused by any slight irregularity in the operation of the valves. Since the advent of the steam turbine, however, hunting troubles which cause a reversal of power have practically disappeared and I very much question if it is now desirable to fit delaying devices to this relay type.

Inverse time-delaying devices, however, could be fitted to the arrangements shown in Figs. 22 and 24, and while these would have delayed action for simple reverse current the operation would be practically instantaneous for differential currents, and this would meet Mr. Clothier's objection to the device. As an example, taking the proportions given for the scheme shown in Fig. 22, a 20 per cent reverse current such as would be obtained by a breakdown between turns of the same phase would represent a current of 0·1 ampere through the current coil of the relay. A 20 per cent leakage current on the generator windings would give at full load a differential current between the transformers of $(7\times 120\ \%)-7\cdot5=0\cdot9$ ampere. We see, therefore, that a 20 per cent leak will cause the relay to develop nine times the torque that a 20 per cent reverse current would do.

In answer to Mr. Brazil I should say that I have always understood and used the term "leakage current" to denote current which flows in one phase and does not return by the other phases, and this independently of the actual current which flows. The carbon-powder resistance might prove helpful in those cases where breakdown occurs close down to the star-point end of the generator winding.

In answer to Mr. Taylor I should say that for the protection of an existing open-ended feeder I should prefer any of the pilot-wire systems. Failing the provision of pilot wires there is nothing better than core-balance protection with overload relays to deal with short-circuits between phases. For existing parallel trunk feeders to the number of two I should recommend interlocked discriminating relays at the source end and reverse relays at the remote end. If the number of trunk feeders in parallel is four or upwards I would suggest that interlocked discriminating relays be placed at each end of the feeders and correct discrimination would be obtained at the substation end for any two out of the four feeders. At the source end correct discrimination would be obtained for all the feeders in the event of a fault. A similar arrangement could be applied to a number of parallel interconnectors. Alternatively, ordinary overload relays connected differentially could be employed and very satisfactory protection given for a group of, say, four parallel feeders or interconnectors. Two parallel feeders can be connected and run as a split-conductor unit, and this has been done to a considerable extent on certain of the larger power systems. So far as I am aware, most protective systems do not depend for their operation on faults between phases on the supposition that the fault will partially involve a connection to earth. Either the split-conductor or pilot-wire arrangement will operate correctly even should the fault between phases involve no leakage current to earth. Core-balance gear may operate with faults between phases, but it is not always safe to assume that the earth current will also be involved. I agree with Mr. Taylor that overload relays on either Merz-Price or split-conductor gear should have settings which would make them last-resort emergency devices.

Mr. Wilson raises the same point as Mr. Cowie regarding the non-operation of the discriminating relays protecting parallel feeders on the occurrence of a fault close to the remote end. The split conductor is called upon to operate under the same conditions and it is not suggested that it is incapable of dealing with this fault. I have dealt with this point in my reply to Mr. Cowie. My reason for showing Fig. 13 is that it secures the protection with a minimum of pilot wires. I do not suggest that Fig. 13 is as satisfactory as Fig. 35, but it provides definite protection at less cost. If there are several feeders in parallel we can install the same type of relay at each end of the feeders, and adequate protection is secured without pilot wires and without requiring the potential of the system. Fig. 13 requires only three pilot wires in the case of a three-phase application.

In reply to Mr. Marshall, where two single parallel cables are in service I should prefer to protect them with interlocked discriminating relays rather than to couple them together as one unit and protect them on the split-conductor principle. Each cable has its switch and no change is necessary other than the addition of the protective gear. In the case of a fault on one cable uninterrupted supply can be given, which is not the case when the cables are coupled together as one unit. Mr. Marshall has evidently misunderstood me regarding the question of producing definite unbalance in the protective gear circuits. If a balance is required definite points have to be exactly maintained through a wide range of conditions. If unbalance is required as an essential feature of the protective scheme it is immaterial whether this is 5 per cent under one condition or 7 per cent under another. While this unbalance holds in one direction it stands for stability,

and this approximate condition of unbalance is, I maintain, not difficult to obtain.

Regarding the combined cable protective and detective system which is associated with Mr. Richards' name, I think it is a pity to go to the expense of incorporating an auxiliary conductor in the cable to protect only against faults to earth.

The point which Mr. Goslin raises regarding the effect of induced current in the pilot wire on overhead systems has long been a source of trouble on long transmission lines. These troubles were early manifest on adjacent telephone lines, and it is only to be expected that they will influence the protective gear equipment when the pilot wires for the latter are strung with a fair separation on the same poles. Transposition at regular intervals should reduce the effect of induced currents, although it may not entirely eliminate it. Induced current in the pilot wires should have no effect on the arrangement shown in Figs. 35 and 37. This current will flow entirely through the restraining coil and divide itself between the dummy circuits and the transformers. As the current flowing through the operating coil will represent only the portion which flows to the dummy circuit the pull of the restraining coil will be the greater and the stability should actually be increased. Regarding the 10 per cent lever bias representing a true bias of 5 per cent, this arises through the pull of the plungers increasing as a square law, consequently, if there is a slight current difference between the coils a large differential pull is exerted by the plungers. The fault settings shown in Fig. 21 represent what it is possible to obtain with robust relays of the dynamometer type. The actual bias employed for this curve was 1 per cent at full load.

DUPLEX WIRELESS TELEPHONY: SOME EXPERIMENTS ON ITS APPLICATION TO AIRCRAFT.

By Captain P. P. Eckersley.

(*Paper first received* 17 *January, and in final form* 29 *June, and read at a* Wireless Sectional Meeting of The Institution, 17 *March*, 1920.)

1. Introduction.

(*a*) *Origin of experiments.*—This paper deals with experiments on duplex wireless telephony for aircraft carried out at the Wireless Experimental Establishment of the Royal Air Force.

It was suggested by the R.A.F. in the field that duplex wireless telephony sets might be fitted to kite balloons so that observers could keep in constant touch with a central exchange even though the balloon was being towed to and fro to avoid hostile shell fire. Experiments were therefore started in 1917, by Major Whiddington, R.A.F., and were handed over to the author in the early summer of 1918. Although one officer was primarily responsible for the progress of the experiments many of the solutions of the problems were founded on the suggestions of other workers at Biggin Hill.

Much work has been done on duplex wireless telephony, throughout the world, but the author is not aware of any system other than those outlined herein directly applicable to aeroplanes or airships.

(*b*) *Distinction between duplex wireless telephony and switched wireless telephony.*—With true duplex telephony sets the operator should be able to send and receive simultaneously using the wireless telephone exactly as he uses the ordinary wired telephone.

All wireless telephony transmission depends for its action upon the possibility of modulating the intensity or frequency of continuous waves sympathetically with the voice. In order that such waves shall carry over long distances, the amplitude of the aerial currents producing them must be very large compared with the currents which can be detected by the receivers. The relatively powerful oscillations therefore interfere disastrously with any receiver coupled to the radiating system, and the problem of simultaneous reception and transmission is to protect the receiver, without detriment to its sensitivity, from these oscillations. To indicate the magnitude of the problem it is necessary to realize that the standard aircraft transmitter deals with energies some 10^6 times greater than those dealt with by the receiver.

In most commercial wireless telephony sets of to-day a hand-operated switch completely dissociates the receiver from the aerial system when transmitting and switches off the transmitter when receiving. This may be referred to as *switched wireless telephony* in contra-distinction to *duplex wireless telephony*.

Conversations with switched wireless telephony sets suffer from the same disadvantage as conversations with speaking tubes where simultaneous transmission and reception is impossible.

(*c*) *The practical value of duplex wireless telephony.*—It is an undoubted fact that an interchange of thought between two participants in a telephone conversation is far more rapid if one conversant can at any moment interrupt the other. This so-called 'chipping-in," which is only possible in a system with devices for simultaneous sending and receiving, acts as an encouragement to the speaker, making him confident that the trend of his thoughts is being followed. While using a switching system the sensation of speaking into the microphone corresponds rather to that of a conversation in an unmastered language; one usually misses the answers and one is never certain that one has been understood. Without the possibility of interruption a conversation loses coherence and the transmission of long messages may often entail long and irksome repeats. Thus time is lost, and considerable difficulties sometimes arise because both stations are on 'send" or "receive" simultaneously

Duplex wireless telephony has great practical value inasmuch as it obviates the necessity of using switches and, furthermore, opens up the possibility of unskilled communicants being as readily put into touch with one another as they are with wire telephony. A subscriber to any ordinary telephone line would, by the aid of duplex wireless telephony, be able to call up an aeroplane in flight or a ship at sea.

(*d*) *The electrical problems in duplex wireless telephony: General methods of solution.*—The solution of the problems of arranging a circuit for true duplex telephony lies in devising some form of circuit which will protect the receiver, without detriment to its efficiency, from the effects of the relatively powerful high-frequency alternating currents generated by the transmitter.

A number of solutions have been suggested. For use on the ground two aerials, one for transmission and one for reception, may be employed placed at right angles and spaced more than one-quarter wave-length apart. Two different wave-lengths are then used. This is obviously not applicable to aircraft.

Frames at right angles have been suggested, but it is questionable whether this would be very practicable on aircraft.

Balancing systems with two aerials, one receiving and the other transmitting, in which the effect of the transmitting aerial on the other is balanced against some equal and opposite effect purposely communicated through circuits under the operator's control, have given considerable success for ground work.* For aeroplanes such arrangements might not be successful, owing to the difficulty of carrying two aerials so rigid

* Alexanderson: *Proceedings of the Institute of Radio Engineers*, vol. 7, p 363

as to enable the necessary state of balance to be maintained.

There is another general method of protecting the receiver in which the earth path is split, and it is arranged for all the transmitter currents to pass to earth through one path and all the received currents through the other. The receiver can then be coupled to the path which is free from the transmitter oscillations, where it will be only influenced by the received energy. This system practically presupposes two wave-lengths, the action depending upon the proper choice of the impedances of the two paths. One or two aerials may be used.

If perfect protection is afforded the receiver, "chipping-in," i.e. simultaneous reception and transmission, is possible and such an arrangement constitutes a true duplex wireless telephony system—using standard transmitters and protected receiving circuits.

In order to overcome the criticality of the balancing system, a compromise is possible wherein the transmitter only oscillates when the operator is actually speaking, the receiver being meanwhile paralysed. One aerial and one wave-length is then theoretically possible. This constitutes no more than an automatic switching system, no "chipping-in" being possible. The name "quiescent aerial" has been given to this type of transmitter, and the whole system may be described as "automatic duplex wireless telephony." No "chipping-in" will be possible, but the switch is dispensed with.

Quiescent aerial transmitters however have to be rather complicated in order that they may transmit good speech.

If, however, transmitters are arranged with a small permanent oscillation flowing which is increased sympathetically with the voice, they give, with very simple circuits, good speech. Thus such transmitters can be arranged with a receiver which is protected only from the small permanent oscillations necessary for good speech. "Chipping-in" will again be impossible except over short ranges, but the arrangement has the advantage of simplicity in the transmitter circuits, and, as the receiver is given more and more protection, it becomes more and more a true duplex circuit.

This type of transmitter has been given the name 'augmented oscillation transmitter," and, when used with a partially protected receiver system, constitutes a "partial duplex system."

The augmented oscillation transmitters used with their appropriate receiver circuits are obviously applicable to aircraft, while the quiescent aerial system is applicable to kite balloons and airships but possibly not aeroplanes because the external noise picked up by the microphone might be enough to induce a permanent oscillation in the aerial.

A description is given below in some detail of the methods by which the above general conditions have been fulfilled, and the practical and theoretical advantages of each arrangement

2. Automatic Duplex Wireless Telephony Systems.

(*a*) *Quiescent aerial transmitters.*—The first suggested method embodied a compromise in which the receiver was not specially protected but the powerful oscillations necessary for transmission were only created when actually speaking, the receiver being simultaneously paralysed but returning automatically to its normal sensitivity directly transmission ceased. The name "quiescent aerial" has been given to this type of transmitter. This automatic duplex system has little superiority, as regards the user's point of view, over switching systems. The interest in this type of transmitter lies not so much in its practical possibilities as in the insight its behaviour gives into methods of telephony control generally.

(*b*) *Voice controlled high-tension transmitter.*—This type of quiescent aerial transmitter was first proposed by the General Electric Company of America and later independently by Major Whiddington, R.A.F. It is a direct outcome of the choke control system described

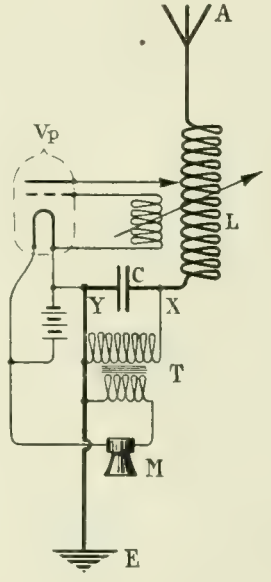


Fig. 1.

by Major Prince.* Instead of modulating, by the voice, the intensity of a continuous source of power supplied to the oscillator, as with choke control, power is only supplied to the oscillator when speaking and is governed in intensity by the microphone. Thus, only when speaking are oscillations generated.

Fig. 1 shows the connections for producing oscillations in the aerial circuit A L C E by the valve V_p. Only when a difference of potential is applied between the points X and Y (X having the greater positive value) will the system generate oscillations. Furthermore, the amplitude of these oscillations is directly proportional to the voltage between X and Y.

If transformer T is therefore connected as in Fig. 1, then, when the current in its primary is varied by the microphone M, the resulting secondary voltages across X and Y will set the high-frequency circuits into oscillation; these oscillations occurring only during speech intervals and being governed sympathetically by the voice

The potentials across X and Y, using only an ordinary

* *Journal I.E.E.* 1920, vol. 58, p. 377.

microphone transformer, will, however, be too small for any but very low-powered sets, and it is therefore essential to amplify these voltage variations by means of a control valve V_c and transformer T (Fig. 2).

Thus in Fig. 2, when the microphone M is spoken into, the grid of the valve V_c varies in potential owing to the action of the transformer T_m, causing larger energy changes in the anode circuit, which results in amplified voltage variations across the secondary of T, and hence the appearance of proportional oscillations in the high-frequency circuits A L C E.

The potential variations across T constitute the sole source of voltage supply to the oscillator, and high-frequency currents therefore will only be created when speaking.

(*c*) *Theories to explain poor speech-quality in the quiescent aerial transmitter.*—The chief trouble experienced was that the quality of the radiated speech was much

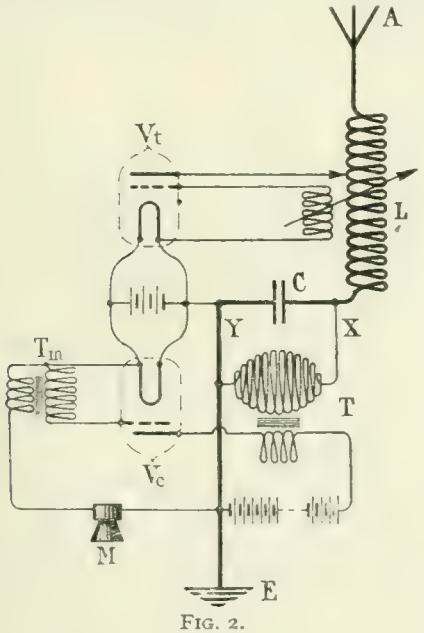


FIG. 2.

worse on the whole than that given by transmitters using standard methods of control, e.g. the choke control proper. It lacked a certain mellow roundness, was sometimes broken and peaky, and was above all very variable; sometimes almost good, at others very bad, depending upon critical adjustments of the circuits. Even at its best it was never good enough for practical needs.

Sensitive microphones improved the speech quality, good voltage amplifications of the microphonic variations were essential, and paralleling the valves dealing with the high-frequency currents improved matters, but none of these precautions made the system practicable.

One prominent fact, however, stood out; namely, that the application of a small permanent voltage in series with the secondary of the transformer T (Fig. 2), just enough to keep the system oscillating very feebly, at once completely changed the speech quality from bad to good.

There have been various theories to explain the poor speech quality, the first of which may be called the voltage threshold theory.

Fig. 3 represents the voltage applied between anode and filament of an oscillating valve plotted against the resulting high-frequency current. It will be seen that the curve does not pass exactly through zero and that a voltage V_t must be applied before the system will oscillate, however feebly. It was suggested that initial small voltage variations corresponding to the preceding consonants of certain words might not exceed V_t and that they would therefore never appear as high frequency oscillations. A battery, the voltage of which was equal or slightly less than V_t was, therefore, connected in series with T, but no improvement in speech quality was noticeable until the value of the battery voltage exceeded V_t by an amount δ V, just enough to keep the system permanently but feebly oscillating. This theory then does not explain the poor speech quality with quiescent aerial transmitters.

Considerations of power input.—In a report on choke control by Captain N. Lea of the Wireless Experimental Establishment, R.A.F., it was suggested that quiescent aerial systems failed because the power input was not directly proportional to the voltage input. The relationship is represented by $P = K V^2$. Thus a voltage input of V_1 volts represents a power output of P watts, but an input of $2 V_1$ volts an output of 4 P watts. But

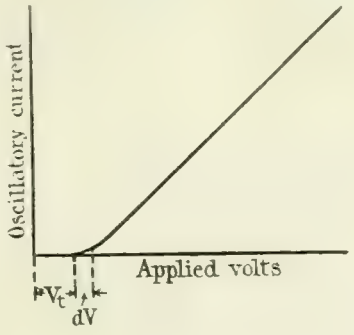


FIG. 3.

assuming the intensity of the received speech to be proportional to the transmitted power, a strict proportionality should be maintained and the received speech should faithfully represent the input voltage intensities, which in their turn are directly governed by the voice.

Time-lag theory.—It can be shown experimentally that a time interval, amounting in extreme cases to 3/100ths of a second, elapses between the instant of application of the voltage to the high-tension terminals of a valve oscillation generator, and the time of appearance of oscillations in the high-frequency circuits. This interval is reduced the greater the intensity of the applied electromotive force. Furthermore, the oscillations persist an appreciable time after the withdrawal of the voltage pulse which created them.

Thus in the case of the voice-applied high-tension quiescent aerial system discussed above, the initial speech consonants, which produce relatively high-

frequency and small-intensity voltage variations in the control circuits, may produce no corresponding high-frequency oscillations, since their time of endurance is small compared with the total time lag of the oscillatory circuits. Preceding consonants are the most important factors in determining good speech quality, and their loss alone is sufficient to make articulation imperfect.

The application of the small extra voltage which maintains a small permanent oscillation in the high-frequency circuits may not only minimize the lag but make it constant for different intensities of applied voltage.

It is true that only one-half of the speech wave is being used, and it might appear at first sight that the negative kicks, which are as intense as the positive, would stop the system oscillating and cause lag effects. It must be realized, however, that there is a time lag in stopping the system oscillating, and that the time of endurance of the negative pulse may be too small to be effective. There is also a further reason why the small extra high tension is effective in producing good speech. In Figs. 4*a* and 4*b* are shown rather detailed examinations of the low-frequency current and voltage changes in a control system similar to that shown in Fig. 2.

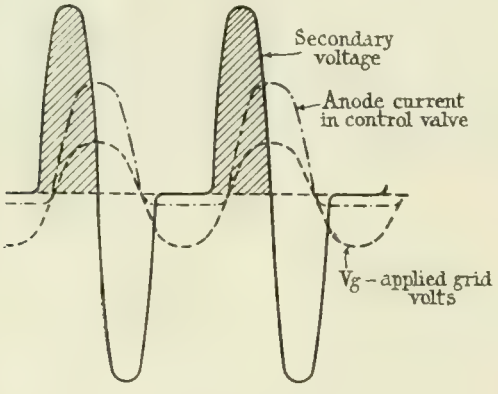


FIG. 4*a*.—Secondary of transformer T (Fig. 2) applied to oscillator.

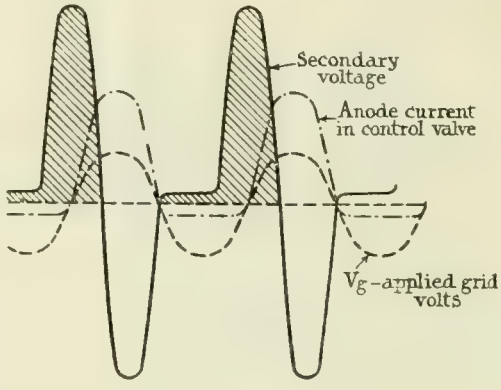


FIG. 4*b*.—$V + d\,V$ applied to oscillator in series with secondary of transformer T (Fig. 2).

The curve V_g (Fig. 4*a*) represents the voltage applied to the grid of the control valve V_c (Fig. 2) and is for clearness' sake represented as a sine curve. The resulting anode-current curve represents the current changes in the primary of the transformer T (Fig. 2). It is assumed that there is a permanent negative potential on the grid so that the excursions of the grid voltage in the negative direction produce little or no current change in the anode circuit. This produces asymmetry of the voltage changes in the secondary of the power transformer T (Fig. 2) and it appears that, during the period of negative excursion of the control valve grid voltage, no voltage is generated in the transformer T.

The shaded loops are alone effective in producing oscillations in the high-frequency valve circuit, which derives its power solely from the transformer T (Fig. 2). During the time of a complete cycle of applied grid voltage only one-quarter of this period is effective in producing oscillations in the wireless circuits.

But now suppose a voltage ($V_t + \delta V$) is applied in series with T (Fig. 2) just enough to maintain a slight oscillation in the high-frequency circuits. This case is shown in Fig. 4*b*, and the shading shows the periods during which the oscillations are maintained. At once the ratio of effective to non-effective periods is as 3 to 1, i.e. 9 times greater than when ($V + \delta V$) was not applied.

The period during which the negative kick tends to stop the system oscillating is now very small; so small probably as to be negligible.

When a permanent positive potential is applied to the control valve grid these conditions are not present. It was noticed that the speech quality, even with a permanently oscillating high-frequency system, was entirely spoilt unless a negative potential was applied to the control valve grid.

The whole theory is admittedly incomplete without further experimental corroboration, but it was impracticable to investigate the subject more deeply during war time, and quiescent aerial systems were abandoned for other circuits which seemed to give more promise.

(*d*) *Excited grid systems.*—Later on, however, after the declaration of the Armistice, the author experimented with a circuit which it was hoped would minimize the lag and open up the possibilities of quiescent aerial systems once more.

The lag in the valve type of oscillation generator is probably due to the time taken for the energy to build up between the grid and anode coils. To overcome this, therefore, the grid voltage of the power valve was continuously varied in potential from an outside source at a period corresponding to the natural period of the aerial circuit.

In Fig. 5 the circuit L_x C_x oscillates continuously, these oscillations being in tune with the aerial system A L C E. Coupled to L_x is an aperiodic coil which, due to the oscillation in the closed circuit, varies the voltage periodically between the grid and filament of the power valve V_p. There is no coupling between P and L. When a potential difference is applied between X and Y the aerial system is set into oscillation. There should therefore be no lag in building up the oscillation due to the interaction of the reaction and anode coils, as the grid is con-

tinually and uniformly varied in potential of the correct amplitude and period.

The speech control circuits correspond exactly to those shown in Fig. 2, the only difference in the whole arrangement being that the grid of the power valve is continuously excited from an outside source, instead of being automatically energized from the interaction of aerial inductance and reaction coils.

The circuit gave very good speech, but was found to be not a truly quiescent aerial transmitter, inasmuch as a continuous oscillation was set up in the aerial due to the capacity effect between the grid and anode of the power valve V_p (Fig. 5). When this effect was reduced to zero the speech quality became worse, although it was an improvement on any other tried system. Speech quality improved with brighter filaments.

A further experiment was tried in which two power valves were used, each dealing with the different halves of the speech wave. Blurred speech resulted directly

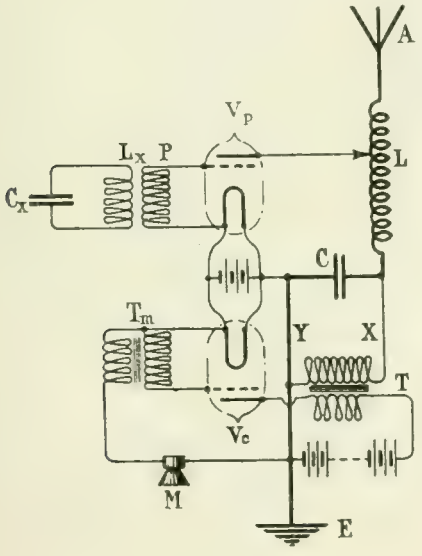


FIG. 5.

the second valve was introduced, whereas with one the voice was quite fairly clear. This was probably due to the two sets of oscillations generated by each individual valve becoming intermixed just around the point where the speech voltage was zero, showing that one oscillation was persisting while the other had already started.

The above discussion points to the conclusion that the quiescent aerial system fails owing to the non-instantaneous response of the high-frequency system to the fleeting high-tension pulses applied to it, and that there is a persistence of oscillation after the high-tension pulses have ceased. This trouble may be overcome by maintaining a small permanent oscillation which is increased in intensity according to the intensity of the voice.

(*e*) *Receivers for automatic duplex wireless telephony.*—Some experiments were carried out with limiting valve circuits and "paralysis" methods, the receiver circuits being set to the same wave-length as the transmitter and coupled to the same aerial, but it was found difficult satisfactorily to prevent the receiver picking up high- and low-frequency disturbances from the transmitter while the latter was active, resulting in deafening noises in the receiving telephones when speaking into the microphone. No satisfactory cure was found for this trouble.

(*f*) *Conclusion to automatic duplex systems.*—Any circuits which are devised to make quiescent aeria transmitters must be arranged to overcome the lag effect. Even if circuits are so devised, they will not materially help the progress towards true duplex systems, since the question of protection of the receiver still remains. As the receiver must be protected from the oscillations it is no longer necessary to use a truly quiescent aerial transmitter; an augmented oscillation transmitter will do as well.

Automatic duplex wireless telephony was actually carried on over short ranges using limiting receiving valves, distuned receiver circuits and various forms of quiescent aerial transmitter, but the conversations usually degenerated into acrimonious shouting competitions which did little more than deafen the sender by his own voice.

3. True Duplex Wireless Telephony Systems.

(*a*) *Protected receiver circuits.*—In a protected receiver system there is no novelty in the transmitter, which may be of any known type relying for its action upon the steady continuous production of continuous waves controlled in amplitude by the voice and maintained at a constant amplitude even when the operator is not speaking.

This ensures the production of good transmitted speech quality. The intrinsic problem of the arrangement is to ensure that the receiver shall not suffer any great loss of sensitivity due to the persistent presence of the relatively large alternating currents generated by the transmitter which may be connected to an aerial very close to the receiving aerial or to a common aerial.

(*b*) *Rejector circuit. Two aerials two wave-lengths.*—The first suggested method embodied a standard type of telephone transmitter oscillating continuously and connected to an aerial separated by only a few feet from the receiving aerial. The received wave-length differs from the transmitted wave, and all that is necessary is to make an extremely selective receiver, which will be influenced by disturbances of one single frequency and by no others, whatever (within limits) their intensities.

Fig. 6 shows an aerial A_t connected to a standard type of transmitter earthed at E, and this constitutes the sending system wherein there are no departures from standard practice.

Let the wave-length emitted be $\lambda\, t$.

The receiving system consists of a second aerial A_r, which, together with L_r, is tuned to a wave-length λ R. A closed circuit K_1 L_2 K_2 is electrostatically coupled to the aerial system by the condenser K_1, and is also tuned by the adjustment of the condenser K_2 to λ R.

When therefore disturbances of a wave-length λ R fall upon the aerial the closed circuit will be set in oscillation.

If a receiver is coupled to L_2 these oscillations can be detected in any standard manner. It will be seen at once that the value of K_1 constitutes the electrostatic coupling of the closed circuit to the aerial. K_1 is adjusted to its largest possible value consistent with sensitivity. The introduction of the inductance L_r allows K_1 to be much larger than if the aerial were aperiodically connected. Forced oscillatory currents will be set up in the receiving aerial by the relatively powerful oscillations in the nearby aerial A_t. These oscillations will pass to earth either through K_1 or through L_2 K_2, dividing in the inverse ratio of the impedances of these two possible paths. If K_1 is large its impedance to forced oscillations of any period differing from λR will be very much smaller than that of L_2 K_2, and so nearly all the forced oscillations will be diverted from L_2 K_2 and the actual receiver will be left undisturbed. Any forced oscillations passing to earth through L_2 K_2 will be further prevented from influencing the receiver by the loose coupling between L_2 and L_3.

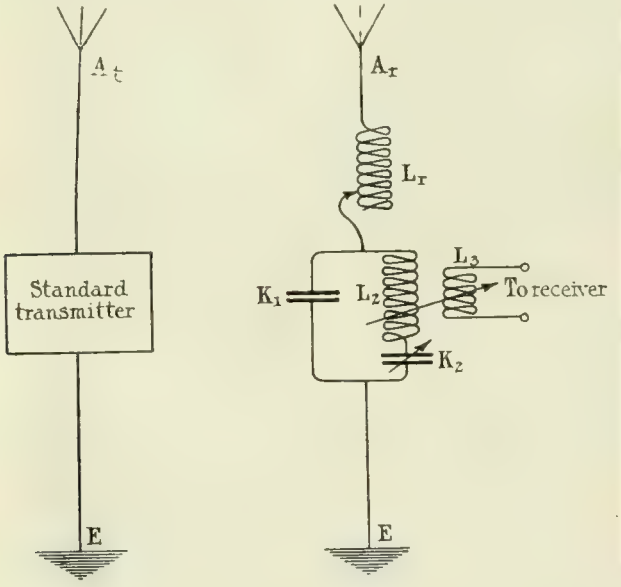


Fig. 6.

A safe value for K_1 is 0·003 mfd. Using an aerial of capacity 0·00025 mfd. K_2 can be made to vary between 0·0005 and 0·001 mfd. depending upon the range of wave-lengths desired, and L_2 is wound to suit the value of the received wave-length.

The circuit, in the author's opinion, is novel, although it may appear to resemble very closely other receiving circuits.

Without the inductance L_r (Fig. 6) the arrangement exactly corresponds to the well-known "flywheel" circuit which may be used for the reception of long waves. But this flywheel circuit will not help to achieve duplex working, since the capacity K_1 has to be of the same order of magnitude as the aerial capacity if the arrangement is to be sensitive. This means that the impedance of the pure capacity path to the forced oscillations from the neighbouring transmitter is largely increased, defeating the object of the whole arrangement. The inclusion of the inductance L_r (Fig. 6) magnifies the impulses due to the incoming signal applied to the closed circuit and allows a very much larger capacity to be used for K_1, and hence increases the selectivity of the whole arrangement and makes duplex telephony possible.

No doubt the rejector circuit would fulfil the same functions, but it is claimed that this circuit is an improvement on the rejector, inasmuch as it reduces the number of necessary adjustments.

An attachment was made up for experimental form for demonstration and test purposes. This attachment is designed for wave-lengths between 400 and 500, or 650 and 750 metres. The choice of these wave-lengths was influenced by the receiver ranges which corresponded to those given above. The circuit will work at a difference of 20 per cent between the transmitted and received waves.

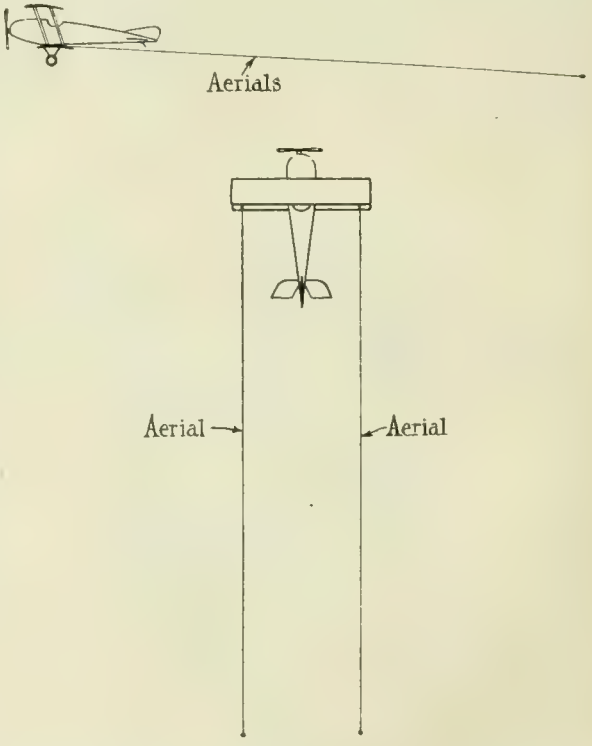


Fig. 7.

The transmitters used were the standard Air Force aircraft wireless telephones and on the average gave 0·4 ampere in the transmitting aerial. The aerials were carried on a common spreader 4 feet across. The forced oscillations in the receiving aerial amounted to about 40 milliamperes and nearly 1 milliampere flowed through the path K_2 L_2 coupled to the receiver. No sign of loss of sensitivity was noticed due to the forced oscillations, provided the earthing points of the transmitter and attachment were both connected to the earth at the same point and not made common on the instruments and then earthed through one long wire.

The receiver picked up very little radiated high-frequency speech variations from the nearby transmitter,

but the interaction of the low-frequency circuits gave a comfortable intensity in the head receivers. The electrical overhearing of one's own speech in an aeroplane is very essential as it lends confidence, keeps an automatic check on speech quality, and approximates to conditions of ordinary conversation where one can hear one's own voice.

The author was ordered to test this duplex system between kite balloons and the ground, but this order was countermanded owing to the rapidity of demobilization preventing the maintenance of balloon crews up to full strength. It would have been interesting to find out if the circuit still functioned successfully with the rather peculiar earthing arrangements on the balloon which must differ in electrical behaviour from the common type of earth used on the ground.

The earth on the balloon consisted of a network of wire festooned about the envelope, but not electrically connected to the hawser which holds the balloon captive.

Many successful ground demonstrations were given with these attachments, and all who used it were impressed with the possibilities of true duplex working.

It is admittedly clumsy, but nevertheless feasible, to use two aerials on aeroplanes. The American machines carried two rather fine wire aerials which trailed from the

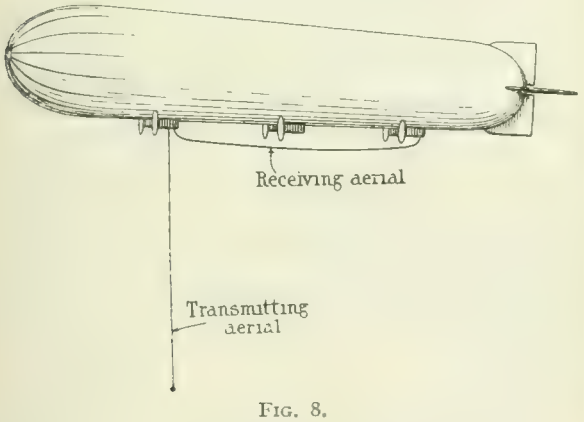


FIG. 8.

wing tips as shown in Fig 7, but which formed one single aerial system. They were not wound up on landing. Zeppelins carried three trailing aerials. This type of duplex working using small power should prove very useful on airships for giving directions for landing, etc., as it needs no critical adjustments. The two aerials might be carried as shown in Fig. 8, and being at right angles and remote from the ground should be immune from interaction.

(*c*) *Divided earth circuit. One aerial and two wave-lengths.*—This circuit is extremely simple in conception and is the outcome of many similar arrangements which did not prove successful for one reason or another. It lends itself very readily for application to aircraft, inasmuch as it uses one common aerial for both sending and receiving.

The connections are shown in Figs. 9*a* and 9*b*. X in Fig. 9*a* is the earth terminal of a standard type of wireless telephone transmitter. Instead of connecting this point directly to earth the earth lead is split into two parallel paths, each containing capacity and inductance. The underlying idea of the circuit is to arrange for all the transmitter current to flow through one path while all the received current flows through the other. The receiver can then be coupled to L_r without being affected by the transmitter.

To achieve this end, the path L_t C_t is tuned to the transmitted wave-length and L_r C_r together with the common aerial circuit is tuned to a different received wave-length. The point X is furthermore arranged to be a node of potential as regards the voltage distribution of the transmitting system, so that there is no tendency for current to be forced into the path L_r C_r.

Let C_a be the capacity of the aerial and L the common aerial inductance. If we suppose the path L_r C_r to be disconnected, then the transmitter currents will flow through L_t C_t. If L_t C_t is made equal to L_m C_a the

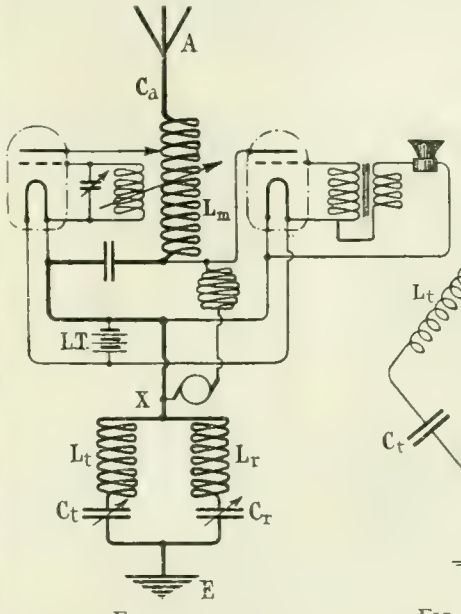


FIG. 9*a*.

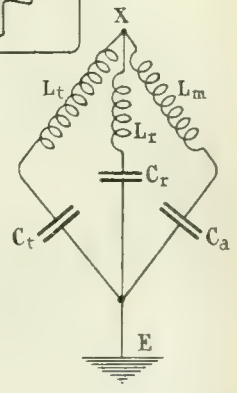


FIG. 9*b*.

wave-length emitted will be the same as if X were directly connected to earth. Furthermore, the point X will be node of potential since the system as a whole forms an alternating-current bridge (see Fig. 9*b*, where C_a is drawn as a condenser) which is balanced, making the points X and E of the same potential when C_a L_m $= C_t$ L_t.

A condition of balance is therefore obtained by adjusting the radiated wave-length with the path L_t C_t added to be the same as when X is directly connected to earth. If now L_r C_r is connected in parallel with L_t C_t there is no insurance against the possibility of the balance being upset, as the whole circuit has two degrees of freedom and may oscillate with a period governed by L_t C_t or L_r C_r or a combination of both. It is therefore necessary to prevent the valve oscillation generator from producing oscillations other than those of a definite frequency governed by the values of C_a, L_m, L_t and C_t, and corresponding to the natural time period of the aerial in series with L_m, L_r and C_t.

This can be done by introducing a coupled circuit between L_m and the oscillation generator, or, more simply, by tuning the reaction in the power valve circuits.

Thus, by limiting the degrees of freedom of the oscillator to one, the connection of $L_r C_r$ between two points X and E, of the same potential, cannot disturb the system and no current will be forced in the path $L_r C_r$.

It is nearly impossible to find a quite perfect node, and so a very small proportion of the current is actually forced into the path $L_r C_r$. However, the greater the difference of wave-length the less current will be forced into $L_r C_r$, since the impedance of this path is reactive, while that of $L_t C_t$ is only resistive to the oscillations produced by the transmitter.

The circuit has, however, two degrees of freedom as regards the receiver, but this is unavoidable for any system using one common aerial and two different wave-lengths. But inefficiencies in reception are not so serious, thanks to the introduction of the multi-valve amplifier with reaction circuits.

It is better to make L_t small and C_t large in order to attain good balance. Also, in order that the impedance of L_r and C_r may be large as regards the transmitter oscillations compared with $L_t C_t$, L_r should be large and C_r small.

By introducing tuned stoppers in the two earth paths Fig. 9*a* the frequencies in the two paths can be made more nearly equal.

Using $\frac{1}{2}$ ampere in the aerial and tuned stoppers the two wave-lengths could be brought within 10 per cent of one another; without stoppers this had to be increased to 20 per cent.

The loss of sensitivity of the receiver is considerable if the wave-lengths approach one another too nearly.

The receiver used was a three-valve low-frequency amplifier employing reaction. The behaviour of the circuit on an aeroplane is questionable, as the node point might be upset badly by the variations in aerial capacity due to sudden turns or dives.

The divided earth system has been successfully demonstrated to numbers of officers in the Air Force, but has not up to now been used in the air. It has the advantages of employing standard receivers and transmitters, using only an attachment to convert these from switching circuits to true duplex circuits.

4. Partial Duplex.

(*a*) *Combination of foregoing circuits.*—It has been shown that a truly quiescent aerial transmitter with the addition of some arrangement to maintain a very small permanent oscillation will transmit good speech quality. In this case a very small oscillation is permanently flowing in the transmitter and the speech voltages are arranged to increase the intensity of these oscillations according to the intensity of the voice. This may be called an "augmented oscillation transmitter" in contradistinction to a quiescent aerial, or again a steady output transmitter.

If such a transmitter is used in combination with a receiver, protected wholly from the small permanent oscillation, but with imperfect protection for greater amplitude, partial duplex is possible. It will be a very simple matter to protect the receiver against the effects of the small permanent oscillation, but the protection may not be so effective actually when speaking, so that quick chipping-in and true duplex could not be possible.

Systems such as this, however, would represent a considerable advance beyond present switch-operated arrangements, besides being easy to handle and not very critical.

5. Subsidiary Problems.

There exist other problems both from the point of view of the maintenance of communication between various stations and from a purely electrical point of view.

The adoption of two wave-lengths, one for transmission to and the other for reception from a remote station, has many practical disadvantages. If there are more than two stations it is necessary for each to receive on a different known wave-length. Provided this is done, any one station can by calling up another on its known received wave get into immediate communication. This becomes, however, cumbersome where there are a great many stations, as it presupposes a large gamut of wave-lengths, and needs furthermore complicated wave-length-changing switches at each station.

For aircraft work it might be arranged for each air set to transmit on a wave-length λ_1 for which all ground stations should listen in, while the ground stations would transmit a wave-length λ_2 to which all aircraft receiving sets would be tuned. This would mean that ground stations could not intercommunicate, nor for the same reason could aircraft talk to each other. Ground stations, however, might use a switching system for communicating with one another on the aircraft transmitting wave, and aeroplanes would have to forgo the problematical advantages of talking to each other.

The jambing with the two wave-length system is really no worse, since one particular wave-length is only used half the time that it would be with single wave-length duplex.

These practical problems may limit the use of the two wave-length system a certain amount, but nevertheless there are great opportunities for aircraft and ship work awaiting its introduction.

Apart from the practical problems there are electrical problems which must be solved before the system can be readily adopted.

First comes the question of the type of receiver to be used.

In all the foregoing work, note amplifiers in conjunction with a reaction valve were used. They have several advantages for this type of work, since they automatically neglect the effect of oscillations below a certain amplitude. Thus, even though the receiver is not perfectly protected from the oscillations of the transmitter, these forced oscillations do not affect the receiver provided they do not exceed a certain intensity.

This advantage is, however, annulled by the fact that note amplification is not a sensitive method of reception, since no more than three valves can be used owing to distortion, and that this type of receiver amplifies the generator hum to a prohibitive extent.

The high-tension voltage for the transmitter is supplied in aeroplane work from some form of rotary direct-current generator. The low-frequency generator ripple is picked up by the receiver and, being of the order of frequency which the receiver is designed to amplify, is heard abnormally loud in the receiving phones.

If high-frequency amplifiers are used, the noise of the generator ripple is practically annulled, but any sparking at the commutator sets up high-frequency disturbances which drown the signal by appearing as a loud rustle in the telephones. Furthermore the high-frequency amplifier is sensitive to very small oscillations in the aerial circuit and any residue of the forced oscillations not balanced out is amplified and produces what is known as " wipe out," i.e. the receiver becomes completely insensitive due to the saturation of the detector valve. Lastly, the high-frequency disturbances set up in the neighbourhood of the transmitter produce " wipe out," even though the receiver is completely disassociated from its aerial, so that the most perfect balancing systems would be ineffectual in protecting the receiver.

Partial solutions of these problems may, however, be found. Rippleless generators have been designed for telephone work by the use of smooth cores—and sparking can be very largely reduced at the commutator. Further than this, chokes and condensers suitably arranged help to smooth out ripples.

The direct " wipe-out " with high-frequency receivers can be overcome by perfect screening of all circuits by metal covering, but this screening has to be very thorough. In fact a severe critic of these duplex systems says screening will be ineffective until the operator as well is encased in metal earthed clothes.

The wipe-out due to the forced oscillations in the receiver circuits can only be eliminated by more and more delicate balance systems, but practically this must be eliminated by a rigid economy in the use of high-frequency amplification, which means sacrificing sensitivity in the receiver.

Doubtless the best compromise between high and low-frequency amplification must be arrived at by experiment.

In former demonstrations given by the author the problem was begged by using high-tension batteries for the transmitter and reaction circuits with note amplifiers for the receiver.

Conclusion.

The unfinished and somewhat undigested experiments outlined in the foregoing discussion were undertaken at first rather light-heartedly in order quickly to devise some form of duplex wireless telephony which would satisfy the needs of the overseas forces. But as the magnitude of the problem became more apparent, and later when the war ended, the researches were pursued more with the idea of obtaining a comprehensive survey of the whole subject rather than of developing practically one single system.

The deeper theory of the action of the circuits, especially with regard to the quiescent aerial system, has not been investigated, firstly because the needs of the war precluded elaborate research, and secondly owing to the very general nature of the work.

The problem has undoubtedly been under the consideration of engineers since the inception of wireless telephony, and even the introduction of the valve, so powerful an asset in the solution of many difficulties, has not provided any solution of the problem of duplex wireless telephony.

The methods given above, however, may give a certain basis on which to build future work, and this can be the only excuse for detailing them here. Undoubtedly after a little further experimenting certain of the systems are immediately applicable to aircraft, more especially airships.

My thanks are due to the Air Ministry for permission to read this paper, to Mr. R. T. B. Wynn for his help during the course of the experiments, and lastly to Major C. E. Prince and the other experimental officers of Biggin Hill who were largely responsible for whatever small success has been achieved.

APPENDIX 1.

As this subject is to a certain extent new, a new nomenclature is necessary. This nomenclature has been introduced in the text, but a recapitulation may be valuable.

The term " true duplex wireless telephony " therefore includes all circuits which protect the receiver from the most intense oscillations generated by the transmitter so that " chipping-in " is always possible.

The term " partial duplex wireless telephony " includes circuits in which the receiver is protected from a small permanent oscillation generated in the transmitter, this oscillation being increased in value, when speaking, proportionately with the intensity of the voice. The receiver is not protected from the intense oscillations generated when speaking and so " chipping-in " is not always possible.

The term " automatic duplex wireless telephony " includes circuits in which the transmitter only produces oscillations when speaking which automatically paralyse the receiver meanwhile, so that the system resembles only an automatic switching system.

Any type of transmitter can be used with true duplex telephony.

The name " augmented oscillation transmitter " has been given to the transmitter used with partial duplex systems.

The name " quiescent aerial transmitter " has been given to the transmitter used with the automatic duplex system.

APPENDIX 2.

(*Received* 29 *June*, 1920.)

Theory of Wireless Telephony.

It may not be out of place in this appendix to go a little deeper into the theory of telephony generally and particularly to show the reasons for good and bad speech quality. It becomes more and more obvious that the design of the receiver has an influencing factor on the

quality of the received speech and it is hoped this discussion may elucidate certain reasons for this. Another point that this appendix deals with concerns a possibility of the quiescent aerial transmitter, where, by a certain arrangement of circuits, telephony can be transmitted without any component of the fundamental frequency, that is, without a so-called carrier wave.

The high-frequency component can be written as $\sin, p\,t$ where p is $2\,\pi \times$ frequency. The voice introduces a number of lower frequencies which are superimposed on the high frequency. The voice component can be written as $f(t)$ and the high-frequency component sent out as $f(t)\sin p\,t$. But $f(t)$ can be analysed into a Fourier series and written

$$f(t) = A + B\sin q\,t + C\sin 2\,q\,t + \ldots N\sin(n-1)\,q\,t$$

Combining these terms

$$\begin{aligned} f(t)\sin pt &= A\sin pt + B\sin pt\,.\,\sin qt + C\sin pt\,.\,\sin 2\,qt \\ &\quad + \ldots N\sin pt\,.\,\sin(n-1)\,qt \\ &= A\sin pt + \tfrac{1}{2}B[\cos(p+q)\,t - \cos(p-q)\,t] \\ &\quad + \tfrac{1}{2}C[\cos(p+2q)t - \cos(p-2q)\,t] + \ldots \\ &\quad \tfrac{1}{2}N\left\{\cos[p+(n-1)\,qt] - \cos[p-(n-1)\,qt\right\} \end{aligned}$$

Thus it is seen that the effect of modulating the high frequencies with the voice is to introduce new frequencies $(p+q)t$ and $(p-q)t$ and so on, which differ more and

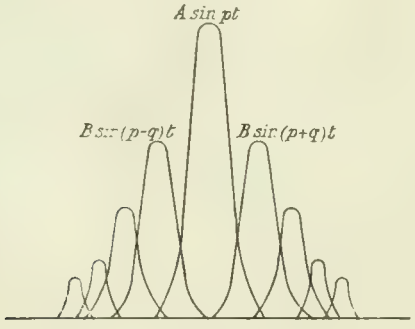


FIG. 10.

more from the frequency of the fundamental $\sin p\,t$ for the higher harmonics of the voice. Thus the higher harmonics of the voice are carried by wireless frequencies which differ in frequency from the fundamental by greater amounts. Drawing therefore a diagram showing the various resonance curves for each separate component of the voice variation we have a family of curves as indicated in Fig. 10.

The centre curve represents $A\sin p\,t$, the fundamental frequency of the transmitter, and exists before the voice is applied. Directly the voice modulation occurs the smaller side frequencies are introduced, and it is the mutual heterodyning of these frequencies with each other and with the fundamental in the receiver that produces speech.

The whole picture has been aptly termed the "crusader and his children," being not unlike the old brasses in churches where the tall crusader is shown standing with his diminishing sons and daughters on either side.

It is essential to realize that perfect speech will only be reproduced if all the family are present in their relative importance. Thus an intensive reaction on the receiver will enhance the size of the crusader relatively to his younger children, and so the higher harmonics of the voice may be lost. Furthermore, the crusader may be so vastly increased in relative size that an actual wipe-out effect may be introduced on the detector valve.

Thus damped high-frequency transformers and flatly tuned receiving circuits are advisable if good speech is to be received, but this presupposes a good strength of signals.

The trouble might be largely overcome by eliminating the term $A\sin p\,t$, called the carrier wave, from the

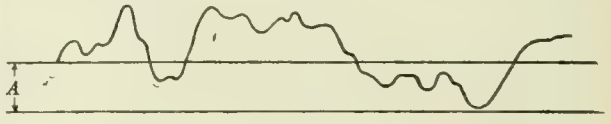


FIG. 11*a*.

transmitter and introducing it as a homodyne (i.e. an independent heterodyne in tune with the carrier-wave frequency exactly) at the receiving end. Thus instead of expending several kilowatts perhaps in producing a carrier wave to travel 500 miles it is possible to transmit only the side frequencies on speaking and supply the carrier wave from the energy of 1 watt a few inches distant from the receiver.

This presupposes a quiescent aerial transmitter since the energy is only sent out as side frequencies when speaking, the normally continuously active carrier wave being suppressed.

The obvious way of suppressing the carrier wave is to make A in the above expression equal to zero. The term A represents the mean value of the modulating amplitude. Thus, in Fig. 11*a*, A represents the mean value

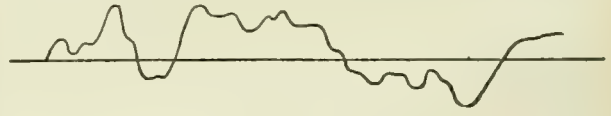


FIG. 11*b*.

of the envelope of the high-frequency amplitudes during successive times. It will be at once seen that the curve is always above the line of zero amplitude and that we can draw a line at an amplitude A that is equal to the mean amplitude of the high frequency when modulated. This is the meaning of the term A in the series representing the components of the speech frequencies. To make A zero therefore the speech modulation must be as much below the line of zero amplitude as above. This is shown in Fig. 11*b*. Such a condition represents a periodic reversal of phase in the transmitted high frequency.

The methods of producing such a reversal of phase, and hence transmission without a carrier wave, are many, but it may be easiest to see the idea if modification of Fig. 6 is described.

Thus suppose instead of one circuit C_x L_x continuously oscillating there are two circuits oscillating in tune

but 180° out of phase and so arranged that their effects on the coil P are zero. Then suppose a permanent high tension is applied between X and Y. If perfect balance between the two closed circuits is arranged no aerial currents will be set up. Directly, however, the balance is upset and $C_x L_x$, say, predominates, oscillating currents will be set up in the aerial in tune with $C_x L_x$. But if the balance is upset by first augmenting the currents in $C_x L_x$ relatively to the second opposing circuit, and then by augmenting the second circuit above $C_x L_x$, the oscillations in the aerial will reverse in phase depending upon which circuit is momentarily predominating. If again such a periodic upsetting of the balance is caused by the voice, telephony will be radiated. But telephony will be only radiated due to the side frequencies and never due to the fundamental, firstly because it is only the introduction of the side frequencies which will upset the balance, and secondly because, as has been formerly argued, the term A has been reduced to zero.

Some great economies in power might be effected if this system were perfected, but it is still doubtful whether the difficulties of the receiving end will be overcome and also whether with all precautions other effects may not spoil the transmitted speech quality. The whole wave-length may change while speaking, i.e. the wave-length of the homodyne may have to move with the intensity of the side waves and it is still doubtful whether the lag effect may not spoil the speech quality of the necessarily quiescent aerial transmitter. The subject has a theoretical interest and has the germ of a very practical economy for telephony transmission.

Discussion.

Professor C. L. Fortescue: One cannot but admire the persistence and optimism with which the author has attacked the problems described in this paper, especially as the problem must often have appeared to him to be practically insoluble. Particularly is this so when it is remembered that it was proposed to use this apparatus in the very limited space available in an aeroplane or an airship. The whole question of duplex wireless telephony is, I suppose, at the moment the most pressing problem in connection with wireless telephony, and it is probable that most wireless engineers would welcome a solution of this problem with greater enthusiasm than the solution of any other. Apparently, there are only three possibilities. One of them is by using, as the author has shown us, two waves. There are certainly only two possibilities of using a single wave, which is so very desirable. There is firstly the method which the author has mentioned in the paper of a high-frequency Wheatstone bridge arrangement as used by Alexanderson in America. I do not quite know with what success that has been carried out, but looking at the circuits it appears that the adjustment of the balance of the Wheatstone bridge must be exceedingly critical. Secondly, there is the quiescent aerial method. The author has explained the difficulties of this system and has pointed out something of what takes place with regard to the action of the circuits. I think, however, that there is one point which he has not made quite clear. He said that although he was working with only the half waves, the quiescent aerial gives exactly the same conditions as when working with the modulated wave of the oscillating-aerial system. I am not quite clear that the results are the same in each case. It appears to me that in working with the half waves extra harmonics must necessarily be introduced at the receiving end, quite independently of whether the law of the relation between the power transmitted and the voltage applied to the transmitting valve is the same as the law of the power which is rectified by the receiving valve from the incoming waves. The curves sketched in Fig. A and Fig. B will bring out this point. A1 and B1 are assumed sine waves of voltage output from the microphone transformer. A2 and B2 represent the resulting aerial oscillations; and A3 and B3 the current through the telephones at the receiving station. With the quiescent aerial the alternating component of the telephone current is an irregular wave about the line P Q, having sharp corners at X and Y. With the permanently oscillating valve the variations of the telephone current follow a more nearly perfect sine wave about the line R S (Fig. B3). The irregular wave of Fig. A3 means that harmonics have been introduced which are due to the fact that only the half waves are in use. One or two remarks in the paper

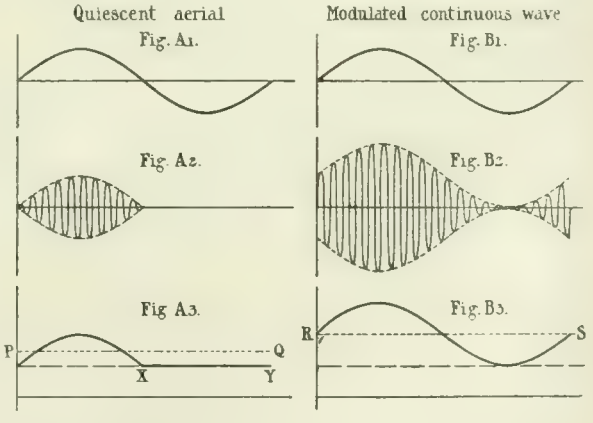


Fig. A. Fig. B.

rather bear out this theory. There is the observed fact that speech is greatly improved if a small oscillation is continuously passing. That is, I think, because there will be a little rounding off of the corners X and Y of the curve, and thus a nearer approach to the sine wave in the variation of the telephone current than when there is no oscillation at all. Again, if two valves are used working on alternate half cycles, the result is to add on another part to Fig. A3 which will accentuate the sharp corners at X and Y. Instead of going down as it ought to do, to reduce the harmonics, the curve will go up. I think this is the explanation of the observed fact that the addition of the second valve caused

blurred speech. If, as appears to be the case, the difficulty of the extra harmonics is unavoidable, it appears that we have to fall back upon the protected receiver system, and it almost seems as if we are also compelled to fall back upon the two-wave system. The two-wave systems which the author has described are very interesting indeed. I think they are really loosely-coupled circuits in both cases. Fig. 6, for example, seems to me to be an old loosely-coupled circuit using capacity coupling. The author mentions that it is novel, but I believe that in about 1907 a description of almost that identical circuit was published. The other circuit shown in Fig. 9*a* and Fig. 9*b* is somewhat different, but on the whole it is not vastly different. It requires a rather more delicate adjustment for the tuning and is a less flexible arrangement in the matter of coupling. I should like to ask the author whether he has attempted to compare that circuit with a very accurately-tuned loosely-coupled circuit. I think that possibly the results might not be greatly different. The system of using a by-pass tuned to the wave which one wishes to get rid of, and of which this is an example, has been used many times, but personally I have always found it an extraordinarily difficult thing to achieve, because there is the tuning of both circuits, and it is necessary as well to pick out exactly the node for the incoming oscillation that it is desired to receive. At the end of the paper the author gives a list of the difficulties that further experimenters will be up against. I think that list is already likely to deter anyone who has any idea of working on the same subject, but it might even be added to. For instance, considerably improved microphones which will operate quite regularly and uniformly without difficulties arising from variations of air pressure; and receiving and transmitting apparatus having precisely the same laws could well be added. With regard to the latter, if there is not a very close similarity between the laws of the transmitting and receiving valve it is obvious that the variations reproduced in the telephone, quite independently of the difficulty which arises from the tuning of the "crusaders and their family," will lead to added harmonics and to blurred speech.

Captain J. M. Furnival: I should like to ask the author what results he obtained in practice from an aeroplane to the ground, or from one aeroplane to another.

Professor G. W. O. Howe: I have wished once or twice that some of the papers which have been read recently before the Institution describing the technical work done in this country during the war could have been read a year ago, because in reading the Continental and American papers during the last year or 18 months I have been somewhat depressed by the impression that all the work had been done abroad and little if any in this country. We are now beginning to see, however, that a great amount of very valuable research work was done in this country during the war. There are one or two points I should like to ask the author, mainly connected with matters of detail. I do not know whether there is any special object in drawing the winding of some of the transformers as shown in Fig. 2. Is it intended to indicate anything special in their construction? I admire the optimism of the author in experimenting with the quiescent aerial systems. When one remembers that the only electromotive force in the anode circuit is that induced by the microphone current, and that until we speak into the microphone there is no electromotive force at all in the anode circuit, to expect this oscillatory system to build up in the very short space necessary to reproduce initial consonants shows, I think, very great optimism on the part of the experimenters and I am surprised to learn that they got intelligible speech. I cannot quite follow the argument set out in the paragraph at the foot of the first column on page 558. The author there says: "During the time of a complete cycle of applied grid voltage only one-quarter of this period is effective in producing oscillations in the wireless circuits." It is obvious that it is about one-quarter in Fig. 4*a*. Then further on we are told: "But now suppose a voltage $(V_1 + \delta V)$ is applied in series with T (Fig. 2) just enough to maintain a slight oscillation in the high-frequency circuits. This case is shown in Fig. 4*b*, and the shading shows the periods during which the oscillations are maintained. At once the ratio of effective to non-effective periods is as 3 to 1, i.e. 9 times greater than when $(V + \delta V)$ was not applied." I cannot see where the 9 comes in. If the whole period be divided into 12 equal parts, the effective period is equal to 3 parts in Fig. 4*a*, and 9 parts in Fig. 4*b*, so that the effective period is increased threefold. With regard to the nomenclature of the paper—a point to which the author has referred—I wonder whether "duplex" in this connection is not a misnomer. By "duplex" we usually understand two operators at one end and two at the other end working simultaneously in two directions, just as in wireless telegraphy duplex. If a system were ultimately introduced in which a talker and a listener at each end worked simultaneously in two opposite directions, I do not know what we should call it. The distinguishing feature seems to me to be the possibility of interruption: it is an interruptible telephone that we are using here. At the bottom of the first column on page 555 the author says: "Conversations with switched wireless telephony sets suffer from the same disadvantage as conversations with speaking tubes where simultaneous transmission and reception is impossible." If it were desirable in any way I do not see any difficulty in having a tube fitted with both a mouthpiece and an earpiece or in having two parallel tubes, one with a mouthpiece and one with an earpiece. The author also mentions aperiodic coils. I do not think that this is a correct use of the word. These coils are not aperiodic; they are merely untuned. Just above Fig. 9*a* I think the wording might be made a little clearer. The author says: "To achieve this end, the path L_1C_1 is tuned to the transmitted wave-length and L_2C_2 together with the common aerial circuit is tuned to a different received wave-length." If L_1C_1 is tuned to the transmitted wave-length there is no need to say lower down that: "The point X is furthermore arranged to be a node of potential as regards the voltage distribution of the transmitting system." It must necessarily be so.

Flight-Lieutenant H. Leedham: I should like to

say how very desirable it is, so far as those of us who have anything to do with telephony in the air are concerned, that there should be this duplex or interruptible system, and how interested we are to find that so much progress has been made in regard to it. We should like to see further progress towards doing away with the trailing aerial altogether. The trailing aerial cannot be used at any rate in fighting machines, with the result that the wireless telephone will never be very popular in the fighting arm of the Air Force until the aerial is abolished altogether and a frame system, or something of that sort, adopted. I should be very interested to know whether any developments have been made in that direction.

Major C. E. Prince: I quite agree with Professor Fortescue as to the importance of the subject. If we can get true two-way working we shall have made the next great advance in telephony. All the author's suggestions seem to point towards the use of two-wave-length systems, but he has also shown their disadvantages, and I cannot help thinking that there must be some future also for the one-wave-length system, and possibly, as is indicated towards the end of the paper, for the combination of circuits which the author calls the "augmented oscillation" system. If we consider the conditions in an ordinary receiver when we are receiving telephony, there is a small continuous wave falling on the aerial, and the receiver must be to this extent in a state of continuous oscillation. That is a fundamental consideration. Therefore if in any way the continuous oscillation prevents us receiving, it must simply be a question of magnitude. It seems to me that it may be possible to achieve a system in which the "augmented oscillation" transmitter may keep up a weak oscillation, which might be rendered innocuous to the receiver by some such system as backing-off. I have made experiments which seem to indicate something of that sort, and hope that future experimenters will not neglect the one-wave system. I should like to tell Professor Howe that all workers in telephony would be only too pleased if some Greek scholar would invent a practical nomenclature which would satisfy the requirements of this new subject. I was very glad to hear him speak in appreciation of the scientific research of all kinds in regard to wireless which was done in England during the war. I happen to know something about it, and that the work done was certainly not inferior to that of any of the other belligerents.

Professor E. W. Marchant: With reference to the paragraph at the top of page 558 referred to by Professor Howe, the author says that the ratio of effective to non-effective periods is as 3 to 1. As it was previously 1 to 3, the ratio is 9 times as big. I think that is what the author means, but I do not think he has stated it quite fairly. It would be better to say there is 3 times as long a period of operation in one case as in the other. My experience in wireless telephony has been limited entirely to cases in which there was a switched-in telephone. I should like to bear out fully the objections which have been raised to the method by Professor Howe and others; if the duplex system could be made thoroughly satisfactory, it would be a very great advantage. I am surprised that the system in which the quiescent aerial has been used has been so successful. If one looks at the circuits and realizes that the function of the "speech" current in the microphone is to start the oscillations in the valve, it seems most remarkable that the system should have been able to produce sounds in the receiver which at all corresponded to the words spoken into the transmitter. The voltage on the choke coil due to the microphone current has got to start an oscillation, and it must produce an oscillation of a strength exactly corresponding to that voltage in an extremely short time if it is to be perfect. The author has referred to the interval before the oscillations begin, as being something of the order of 3/100ths of a second under the worst conditions. I think it must be very much less than this under favourable conditions, and I should like to ask the author whether he has any records of the quickness of the response of the production of these oscillations to the voltages which were applied. I have seen the very interesting oscillograms published in Major Stanley's book, obtained with a cathode-ray oscillograph which has been developed in France by Dufour, and it seems to me that if some such records could be obtained with this apparatus it would throw a great deal of light on the question. The most promising method at present is certainly the two-wave system. On page 557, where reference is made to the intensity of the received speech being proportional to the transmitted power, I think this would only be true with a "square law" receiver. Most receivers of course, including the crystal detector, do follow the square law. I should like to put forward a possible explanation of the effect of the small varying oscillation in improving speech. If a small oscillation takes place in the grid circuit it would tend to stir up the electrons in the filament and so prepare it for action, that is, the electrons inside the filament are driven out of it, and get to work more quickly than if they have first to be driven out of the filament by the oscillations due to speech.

Lieutenant T. L. Eckersley: There are one or two points in connection with the circuit on page 561 which it may be of interest to mention. The circuit depends for its action on the fact that we have got the oscillation in the aerial at the right frequency to give a node at the position X. The oscillating part of the circuit, that is to say the aerial and the divided earth system, is a system of two-degree freedom, and it is not altogether obvious which of these oscillations will occur in any given case, that is to say whether it is the oscillation we require. If I draw the diagram as the author has drawn it in bridge form (see Fig. 9*b*), the branch $L_r C_r$ representing the receiver, $L_m C_A$ the aerial, and $L_t C_t$ the extra circuit; there are two possible oscillations if these two circuits are identical, one in which X is node and the current goes all the way round, leaving out the receiver, and the second in which the current flows through the receiver circuit and is divided equally between the other two arms of the bridge. It is not altogether obvious why the circuit should oscillate in the particular manner which is required by the author's theory. What determines which of the oscillations shall occur is the damping of the oscillations in these two

circuits. That seems to me to be a point to guard against in using a receiver in this way. If we insert a reaction-type receiver which reduces the resistance of the branch L_1C_1 almost to zero, very likely we should reduce the resistance in this circuit to less than the resistance of the circuit all round, and we get large oscillations in our receiver circuit which will spoil speech entirely. That seems to me to place us rather at the mercy of the receiver, and it is a point which has to be guarded against.

Wing-Commander Warrington-Morris: I wish to congratulate the author on the work he has done for the Royal Air Force in the past and also on his paper. Everyone is agreed that true two-way telephony is essential for future progress, though there are occasions when it is an advantage for pilots not to be able to receive messages from the ground. The elimination of the carrier wave marks a very important advance, and the prevention of oscillations in the transmitting circuit due to aircraft noises should be overcome without much difficulty.

Captain H. J. Round: It is difficult to pick on any one of the many subjects which are opened up for discussion by this paper. With regard to quiescent aerial systems, one form of which is an oscillating system without initial high tension in the anode circuit, the author mentions that the speech is bad and that it is better if an independent oscillator is used. Rather an interesting experiment can be made with tonic train which illustrates to some extent what is happening in the quiescent aerial system. If one transmits with a tonic train, using only the positive half waves of the alternating current (at something like 100 periods), and employs at the receiving end a heterodyne receiver, the result is usually a very bad scratchy sound. As soon as two rectifiers are put in, so that the negative half of the wave is reversed, and pulsating direct current of double the frequency is obtained, the result in the heterodyne receiver is a musical note, although the tone is a compound one. The reason for the difference is, that in the first case each half wave starts up a fresh series of oscillations of the right frequency, but the phase relation of any one series bears no relation to that of the next. The effect is something like that in a series of spark trains produced by a spark transmitter. The double half wave is supplying the high tension to the valve all the time, and although it goes to zero, the time that it remains at that value is so short that the aerial never stops oscillating and consequently the phase remains the same all through a dot or dash. As soon as the high tension is connected to a valve and reaction circuit, the circuit is in an unstable state like a rod balanced on its end. Some small force, no matter how small, is necessary to destroy the equilibrium, and the rate of growth of the current is at first very small if the disturbing force is small. If, however, definite weak oscillations are applied to the system, the growth of current will always be the same for the same force. The weak oscillations act in a way as though they were jogging the memory of the unstable circuit. Of course one can also consider the unstable condition as a series of magnifications and feed backs gradually growing. I think the most interesting subject which has been brought up to-night is that of the "crusader and his children." We have had very many discussions on the question whether an arrangement in which the carrier wave is removed will produce good speech. The advantage of working without a carrier wave is very great. The wireless telephone set used at present has a sensitiveness very much below that of a continuous-wave transmitter. If the radius of reception of a telephone set is 1,000 miles, then the radius with continuous waves would be double this distance. The removal of the carrier wave is really an attempt to bring the wireless telephone up to the heterodyne sensitiveness of continuous-wave telegraphy, and if this could be done the telephone would probably be of much greater service. Of course there is the difficulty in the way that on long waves, of say 14,000 metres, we are spreading over rather a large spectrum, and I do not think any International Convention would permit wireless telephony on such wave-lengths. If, however, the carrier wave can be removed and we can receive on a heterodyne receiver, the distance we could get would be very great even on the shorter waves. Then the question occurs: could we possibly supply a homodyne or heterodyne at the receiving end to replace the lost carrier wave? I have recently had some experiments carried out with the object of seeing what would happen with such a system. The result was understandable speech, but it was not what could be called good speech. It turned out, however, that to do the experiment really well, extreme care had to be taken, and we are going to try the experiment again to see if it will work better under improved conditions. One interesting point in connection with the question of the removal of the carrier wave is, that when one goes further and thinks of the old spark telegraphy, could we have removed the carrier wave in that case and, using the heterodyne, obtained the same results as in spark work? Possibly the non-periodic nature of a spark train would introduce difficulties. Perhaps we could take the whole thing still further, apply it to Morse telegraphy and remove the carrier wave of the Morse. All this points to possibilities in the future for the saving of transmitting energy. My present interest is in duplex telephony on land, using separate transmitting and receiving stations at each end. In this connection, when using valve transmitters I was very surprised how close one could bring the receiving station to the transmitting station. The transmitting stations are of rather small power, the actual radiation from one station being only 40 watts, which amount is, however, very considerable for a small station. At Chelmsford, which is one end of the system, the transmitting and receiving stations are 100 yards apart. The wave-lengths used are about 110 metres, with a difference of only 3 metres between the wave-lengths of the two transmitting stations. With a simple tuning circuit consisting of three circuits in series, and using practically no directional system at all, the signals from the nearby transmitter are entirely eliminated. That is with a difference in wave-length of only 3 per cent, and everything indicates that if directional properties are used the two stations could be brought closer still. The distance being worked over is 20 miles overland, and very sensitive

amplifiers are being employed which give a voltage magnification of at least 500.

Dr. W. H. Eccles: The paper deals with a great variety of topics, and it is valuable not only because it classifies practically all the methods that have been found of use in duplex wireless, but because it gives a considered opinion as to the feasibility and usefulness of each of them. According to rumour the next problem is wireless telephony on the grand scale, so as to eliminate Morse transmission and circumvent in large measure the difficulties due to strays. The present paper is limited to aircraft apparatus, but I hope that those working upon telephony will also consider land and sea stations, and not leave the work in its present stage, although very much indeed has been done.

Mr. H. M. Dowsett (*communicated*): It was somewhat surprising to hear the suggestion put forward during the discussion that the lag of 1/300th second mentioned by the author might be attributed to the valve. I do not think this is implied in the paper. The self-capacity effect of a valve may cause a lag of the order of 10^{-7} second. Also Major Whiddington has demonstrated that hard valves from considerations of electronic mobility may have natural frequencies of the order of 10^{8}, and soft valves may have an atomic mobility giving them natural frequencies as low as 10^{5}. Any one of these figures would of course be affected by the time taken for the valve to build up its oscillations to the steady state, and if we assume this takes place in not less than 10 oscillations, the maximum lag possible for a soft valve containing mercury vapour is not likely to have a greater order than 10^{-4} second, so that any lag greater than this value must be attributable to the valve circuits and not to the valve itself. In the high-frequency circuits employed by the author, the frequency was probably of the order of 10^{6}, and this and the building up of the oscillations would only account for an initial time lag of 10^{-5} second. But the modulating circuit includes a transformer and condenser and will have a very much slower period. The condenser C (Fig. 1) is charged at a rate determined by the oscillation period of the circuit T C, and in Fig. 2 the rate will be further reduced by the lag in the transformer T_m. We can thus account for an initial lag of say 1/1,000th second. But it has been shown that a definite threshold potential is necessary to start valve oscillations, and we have now to assume that the initial potential oscillation applied through the transformer to C does not reach this required value, and that several swings of potential on C take place before it does. If it takes three such swings to build up, then a total lag of 1/300th second would be accounted for.

Captain P. P. Eckersley (*in reply, communicated*): One of the most interesting points raised during the discussion concerned the action of the truly quiescent aerial transmitter. The chief difficulty lies in explaining why the augmented oscillation transmitter gave speech of so very marked superiority over the truly quiescent aerial transmitter; why, in other words, the existence of the very smallest permanent oscillation in the high-frequency circuits gave good speech while systems where the oscillations were wholly voice-created gave noises that were hardly recognizable as speech at all.

There are now three definite theories to explain this. First, in their order of promulgation, there is the lag theory. We have the evidence of direct measurement to show that a lag exists and it is certain that this must militate against the faithful reproduction of the low-frequency energy variations as high-frequency currents, but it is not established why such an effect should be more pronounced with a truly quiescent system than with the augmented oscillation system. The only possible theory is that the lag is variable with the intensity of the applied impulse for truly quiescent systems, whereas the permanent oscillation keeps the lag more constant. The whole theory is weak and cannot explain all the observed facts although the lag has, without a doubt, some influence on the speech quality.

Mr. Dowsett in his remarks points out that the lag effect is not bound up with the valve itself but with the circuits external to it. This was realized and it is definitely stated in the paper, but Mr. Dowsett has clearly shown in detail why the valve cannot be responsible for any appreciable lag. I do not think any special precautions therefore need be taken with the valve itself in stimulating its emission as Professor Marchant suggests.

The second theory, advanced by Professor Fortescue, seeks to explain the effects in terms of the spurious harmonics introduced by the inevitable use of only half the speech wave-form. Such spurious harmonics must indubitably exist, but I think Professor Fortescue's theory fails quantitatively, inasmuch as the magnitude of the small oscillation necessary for good speech need be only 1/1,000th of the voice-produced high-frequency currents. If Professor Fortescue's diagrams are redrawn to such a scale it will be seen that the quiescent system and the augmented oscillation systems differ little in their characteristics. The small "rounding off" produced by so small an oscillation would surely not be effective in producing so noticeable a change in the emitted disturbance.

Captain Round's theory is far more suggestive than either of the foregoing. He shows that while using a truly quiescent transmitter of the type shown in Fig. 2 there is no assurance that the successive phases due to each succeeding high-tension pulse shall follow on in a definite order. Captain Round cites as a parallel example the case of heterodyning the high-frequency disturbances emitted from an oscillator using single or double rectification of the alternating high-tension voltages. In the former case a system is being used in which the phases may obviously become jumbled; in the latter the oscillations never cease and so never change step. The result when listened to on a receiver gives in the former case a hiss somewhat the same as a spark; the latter gives a note. Thus one is a reproduction of the modulating high-tension disturbance, whereas the single rectification and hence the quiescent aerial system give no such definite reproduction. It will be seen that the phase-jumbling theory is borne out by experiment, when it is realized that the excited grid system shown in Fig. 5 gave better

speech. For in this system a permanently oscillating circuit keeps a definite phase relationship among the consecutively emitted high-frequency disturbances, and hence arranges a more faithful reproduction of the speech. Nevertheless, with the excited grid system when a state of true quiesence is obtained the speech is far from excellent, showing that probably the lag effect is coming in.

Turning from the problems of the transmitter to the receiver it must at once be admitted that the circuits described in the paper as "protected receiver circuits" are obvious adaptations of well-known selective receiving circuits. My claim for originality must be abandoned in the case of the circuit given in Fig. 6 and I must thank Professor Fortescue for pointing out my error. The circuits are no more than devices for loose coupling. The method of eliminating the forced oscillations of a different period by using a number of loose coupled circuits in cascade gives surprisingly good results, but is wholly unpractical for aeroplane work. No unskilled operator could manipulate it and it is doubtful if anyone could do so with accuracy while flying. The circuits described in the paper are, however, comparatively easy to adjust—an absolute essential if the system is to be a success for aerial work. Professor Fortescue speaks of circuits such as the one shown in Fig. 6 as difficult to tune, but after a little experience the circuit is really simpler than the Navy rejector which it is well known is a perfectly practical arrangement in operation. Nor does the circuit of Fig. 9 present great difficulties provided the adjustments are made in an orderly routine. The condition for the node point to occur at X, as Professor Howe points out, occurs directly $L_t C_t$ is brought into tune with the aerial circuit; a condition shown either by a wave meter or, more simply, provided the transmitter has only a single degree of freedom, by adjusting the aerial current to its maximum. The wording in the paper describing the divided earth circuit might be improved, but X is certainly arranged to be a node point even though this happens automatically as a consequence of the tuning adjustment. Once the proper adjustment has been obtained it is remarkable how free from forced oscillations the path $L_r C_r$ (Fig. 9) becomes.

Lieutenant T. L. Eckersley has pointed out that there are two degrees of freedom of the circuits of Fig. 9 and that precautions must be taken to make the oscillations take up a period corresponding to the natural period of the path $L_t C_t$ in series with the aerial and not $C_a L_m L_r C_r$. This was pointed out in the paper and the method to limit the degrees of freedom was to use tuned reaction. From the results of some preliminary experiments this is a sufficient precaution, but it must be admitted that reaction on the path $L_r C_r$ was never employed, using a tuned transmitter reaction, although this is quite possible without trouble occurring by means of an independent drive, i.e. the oscillatory circuits of Fig. 5.

Generally speaking then, it will be seen that the most practical solution of the problems lies in using a two wave-length system and an augmented oscillation transmitter. Major Prince has long been an exponent of the single wave-length system, being lured by its practical advantages rather than deterred by its electrical difficulties. These difficulties are at present almost insurmountable. First, good speech must be produced from a quiescent aerial transmitter or, if a permanent oscillation exists in the transmitting circuits, this must be completely shielded from the receiver which has to be sensitive to exactly the same type of disturbance it is desired to eliminate. The only possible elimination method seriously suggested is to "back off" the detector valve until it is again sensitive to a change of strength in the ever present oscillations. This gives bad speech when the backed off permanent oscillations differ in wave-length from the received telephony. If the same wave-length *exactly* was used the received speech might not be distorted, but it would require most delicate tuning to avoid heterodyne. Apart from this, saturation devices and shielding must be introduced to keep the noises due to the transmitter within bounds, otherwise deafening noises will be produced in the receiving telephones directly the microphone is so much as picked up. As Major Prince says, it is merely a question of magnitude, but the whole trouble is the magnitude—the enormously greater power of the transmitter compared with the power dealt with normally by the receiver. Bearing in mind, therefore, that the single wave-length system is vastly superior practically, we must find our way to the ideal as always via a series of imperfections and try to refine the two wave-length system for immediate practical use.

The problems remaining are certainly many and are far from being solved. I once thought they were sufficiently understood to try one of the arrangements described in the paper on an aeroplane, but luckily for my optimism the machine met with an accident the day before the test. Captain Furnival's question is therefore answered and, apart from fitting both a balloon and an aeroplane neither of which got off the ground for a test, no air work was ever done.

The most acute problem is generator noise. It is not merely a question of eliminating a low-frequency disturbance. The small residual oscillations not balanced out from the receiving circuits act as ideal carriers for the generator noise, and present the disturbance in a thoroughly palatable form to the receiver itself.

As regards the operations of microphones on aeroplanes and airships and the other incidentals of switched aircraft wireless telephony, I would refer Professor Fortescue to Major Prince's paper * on the subject, where it will be seen that the problems of aircraft telephony have been largely solved. The further problem of "duplex" is largely unencumbered by such details in the present state of our knowledge.

Flight-Lieutenant Leedham opens up an interesting subject in speaking of fixed aerials. The time, however, is not yet when we can apply duplex to the arrangement. When I left the Services the fixed aerial had never been used for transmission at all. It was merely indicated in the paper that fixed aerials might lend themselves to a two-aerial two-wave-length system,

* *Journal I.E.E.*, 1920, vol. 58, p. 377.

although there would be many shielding troubles introduced due to the short waves necessarily employed. For commercial work at any rate the trailing wire is the most practical form of aerial, although I fully sympathize with Flight-Lieutenant Leedham's desire for fixed aerials for the fighting arm of the Services.

Replying to matters of detail in the paper, there is no subtlety in drawing the transformers one way or another, one was drawn by one draughtsman and another by a second—uniformity would be more desirable. The diagram of Figs. 4*a* and 4*b* is sufficiently obvious to show the ratio of the effective to the non-effective periods, but I agree with Professor Howe that the wording was unduly optimistic. In using the term aperiodic coil I was employing a term very generally in use but it is obviously a misnomer, as every aperiodic coil has a natural period due to its self-capacity.

While thanking Wing-Commander Warrington Morris for his remarks I must disclaim any credit for the methods of transmitting telephony without using the carrier wave. A method for doing this has been patented in America by the General Electric Company, but the theory of the idea is well known. Later experiments have convinced me that the arrangement does not give very good speech, but this may be of course due to some particular practical detail that has been overlooked. I have introduced Appendix 2 on the theory of the subject because it is an interesting point about quiescent aerial transmitters that they can be arranged to transmit without the carrier wave and may need a special receiver with homodyne to perfect the received speech quality.

At the time of writing, no really original suggestion has been given to help the solution of the problem. On the ground the problem yields to more direct methods, and Captain Round has already demonstrated with very considerable success the system he described in the discussion. But such a solution has no value for aircraft duplex working where a solution is so badly needed commercially. The problem is undoubtedly very acute and one that may easily deter us from further plunges, but it may yield to detail improvement, the paper only giving broad lines on which advance might be made and particularly showing what not to do.

THE ELEVENTH KELVIN LECTURE.

MODERN MARINE PROBLEMS IN WAR AND PEACE.

By C. V. Drysdale, O.B.E., D.Sc., Member.

(*Lecture delivered before* The Institution, 15 *April*, 1920.)

The Council of the Institution having decided that the time has now come for the Kelvin Lecture to embrace other fields than those of Lord Kelvin's personal activities, have honoured me with an invitation to deal with the scientific investigations which have been carried out in marine problems during and after the war under the Admiralty at its various experimental stations. Apart from the interest and importance of the subject there is a fitness in coupling it with the name of Lord Kelvin, who did so much for the submarine telegraph and for navigation.

As everyone is aware the late war confronted this country with problems of the gravest character for which it was little prepared, and the submarine campaign soon showed the vital necessity for enlisting the highest scientific talent of the nation in attempting to solve them. The Institution co-operated enthusiastically in these efforts, both by the formation of its Anti-Submarine Committee, and by the great personal service of many of its members in actual experimental work in the Admiralty stations and elsewhere. For this reason it is specially fitting that such details of the scientific and experimental work as may be made public should be brought before the Institution.

Although the problems of submarine detection and of destructive or defensive measures have obviously been of chief importance, the work has naturally broadened its scope, and it has been found that the experience and devices obtained have the most valuable application to navigational problems which are now being energetically dealt with. The work may consequently be considered under four chief heads.

I. Detection.
II. Defence and destruction.
III. Navigational applications.
IV. General scientific research.

Before entering upon details, however, some account should be given of the inception and development of the work.

Before the war, as is generally known, a large amount of valuable scientific work notably as regards radiotelegraphy and torpedo research and development was carried on for the Navy at Portsmouth under H.M.S. "Vernon" and on the outbreak of the war this work was greatly extended, by the aid of a number of scientific men who joined the service, and by the opening of the Mining School at Portsmouth. The work of these establishments does not come within the lecturer's province to describe, and is naturally of a secret character, but it has been of the highest importance to the nation.

During the first year of the war the Government appointed the Board of Invention and Research, a body of prominent scientists and technical experts whose task it was to deal with the flood of inventions and suggestions which poured in from all parts of the country. The President was Lord Fisher. The Board was sub-divided into various sub-committees, of which Section II under the chairmanship of the Duke of Buccleuch was concerned to a considerable extent, though not entirely, with the anti-submarine problem. It comprised Professors Bragg and Rutherford, Messrs. Duddell and Merz, and Sir R. T. Glazebrook; Sir Richard Paget and Lieut. the Hon. Walter J. James acting as secretaries. After inquiring into thousands of proposals the need was felt by this Section of some means of putting the more promising of these to some practical test. In November 1915, two physicists were sent to the Hawkcraig Hydrophone Station (Captain—then Commander—Ryan) to work under the direction principally of Sir E. Rutherford.

In May 1916 the staff was increased to five and Professor (now Sir W. H.) Bragg went to Hawkcraig as Resident Director of Research.

The need of further expansion being quickly felt it was decided to establish an independent station, and in January 1917 Professor Bragg moved with his staff to Parkeston Quay, Harwich. The choice of locality was decided by the fact that Parkeston Quay was an important submarine base at which the scientific staff could come into intimate contact with submarines and their problems.

With the growth of the submarine menace there occurred a process of steady expansion. At the same time other stations primarily engaged in anti-submarine work were established under the Anti-Submarine Department of the Admiralty. In January 1918 the Parkeston Quay Station was, for administrative reasons, also transferred to the Anti-Submarine Department, the Board of Inventions and Research reverting largely to its initial task of examining inventions. At the same time Professor Bragg went to the Anti-Submarine Department as Adviser to the Director of the Anti-Submarine Department, Colonel Eve succeeding him as Resident Director at Parkeston Quay.

In June 1918 a deep-water substation was established at Dartmouth and an inland substation at the King George's Reservoir, Chingford. The station also lent a considerable number of its staff to various other stations, both service and experimental.

At the time of the Armistice the scientific staff numbered about 30.

The history of the Parkeston Quay Station has been dealt with partly because it was the station with which the lecturer has been associated and partly because of its rather novel origin. It marks the commencement of a new official policy—that of inviting the co-operation of academic and technical experts. As has already been stated, however, quite a number of other special experimental stations sprang up.

The Hawkcraig Station, already mentioned, did the pioneer work in hydrophones and, in addition to training hydrophone operators, made important contributions to listening devices during the war under the directorship of Captain Ryan.

The Wemyss Bay Station originated as an offshoot from Parkeston Quay in the autumn of 1917, but became in January 1918 an independent station under the Director of the Anti-Submarine Department.

The Portland Station originated in the work of Mr. Nash (of the Western Electric Co.) on a towed hydrophone of his invention. Its chief work lay principally though not entirely in the development of this hydrophone and the training of operators.

The Lancashire Anti-Submarine Committee was a body of voluntary workers (including Mr. Redfern, Professor Marchant, Professor Miles Walker, Dr. Beatty, and Mr. H. C. Beaver) whose work consisted largely in experimenting on devices originated by its members.

The Shandon Experimental Station was established on the Gareloch in the middle of 1918 by the Clyde Anti-Submarine Committee, a body of Glasgow shipbuilders and other technical experts (Chairman, Mr. Gardiner). Mr. A. B. Field acted as Director. The facilities of the station were shared by the Lancashire Anti-Submarine Committee. Much excellent work was originated, but was too late to reach a service stage before the Armistice.

In addition to those who acted on the Board of Invention and Research or worked (in many cases voluntarily) at the various stations, a large number of men of scientific or technical eminence placed themselves at the disposal of the Board of the various committees.

During the latter part of the war there existed an efficient mobilization of the scientific talent of the nation unique in the history of this country, and rapid advances were being made. Had this scientific force got into its stride in the early days, the history of the anti-submarine war at least might have been very different. Unfortunately such mobilization, like the military mobilization, required experience and much valuable time was lost.

Since the Armistice much of the research and fundamental experimental work has been concentrated at the Shandon Experimental Station, which was taken over by the staff of Parkeston Quay in March of last year. The situation of this station on the side of the Gareloch, which is an almost enclosed body of sea water about 5 miles long by 1 mile broad and averaging 100 ft. deep, is exceedingly favourable for preliminary experimental work and especially for research of a fundamental scientific character.

On the return of Colonel Eve to McGill University in April of last year the direction of the station was taken over by Major J. H. W. Gill, R.E., and since the commencement of the present year it has been in the hands of Captain Massey, R.N., as Senior Naval Officer, the research work being under the author as Scientific Director.

Physics of the sea.—It is important at the outset to have a clear idea of the nature of the problems to be faced. What we are fundamentally concerned with is the generation, propagation, and reception of impulses or disturbances through the sea, which may be either mechanical or acoustic, electrical, magnetic, electromagnetic, thermal, optical, chemical, or possibly radiant in character.

The sea, as being a greatly extended medium of high density and elasticity, affords excellent propagation of mechanical or acoustic impulses, but its relatively high conductivity due to its salinity offers a formidable obstacle to the transmission of all electromagnetic disturbances, except those of the lowest frequency. At the ordinary supply of frequency of 50 $\sim$ per second about 94 per cent of the amplitude is probably absorbed in 100 metres. Optical, thermal and other forms of radiation are rapidly absorbed by it, and chemical action is obviously local and rapidly diffused, so that the problem of detecting the presence of a noiseless submerged body is of a most difficult character.

Unfortunately the difficulty is greatly enhanced by the existence of disturbances which may easily mask the impulses it is desired to detect. As we are mostly concerned with objects within a few hundred feet of the surface, the reflections which take place owing to the great difference in the mechanical and electrical properties of the sea and the air are frequently very serious, and give rise to embarrassing interference phenomena, which are further complicated by surface waves; and the same trouble is produced to a lesser extent by reflections from the bottom or from rocks in shallow water. Added to these disturbances are water noises caused by the waves and by the motion of an observing ship, or the noises caused by its machinery of propulsion, etc., as well as "earth currents" and magnetic storms.

In consequence of these disturbances, it is of little avail to attempt to overcome the limitations imposed by weakness of the source or by absorption in transmission, by increasing the sensitiveness of the observing device. Almost all our energies have to be devoted to the study and elimination of the disturbances, or to methods of discriminating between the source and the disturbances. In the latter respect acoustic methods have a great advantage, as the human ear is very sensitive to variations in quality as well as in intensity of tone, but unfortunately this power of discrimination often fails just where it is most needed, as the sounds sought for are frequently hardly to be distinguished from water noises.

Even assuming the problem of detection to be overcome, it is of little value unless the direction of the source can be obtained, and if possible its range. This introduces a new set of difficulties in which reflection, refraction and absorption play an important part. To take only one instance, the lines of magnetic force surrounding a submarine cable carrying an alternating

current, which according to the ordinary textbooks should be in circles around the cable, are so distorted by the "skin effect" in the conducting water and by refraction at its surface that at a moderate range from the cable they are actually horizontal instead of vertical, showing the futility of relying on them for direction. This will be dealt with more fully later, but enough has been said to show that a new chapter in science has to be written on "The Physics of the Sea," and that we have to go to school again and imagine ourselves living in a conducting or semi-conducting lamina which is almost opaque to the majority of disturbances, acting on electro-magnetic waves as tar does to ripples, so that they are absorbed in a few wave-lengths.

We may now turn to a consideration of the technical problems and results, although it is to be regretted that many of the most interesting and effective devices cannot be described for obvious reasons.

I. DETECTION.

It would take a large volume to describe the various schemes which have been proposed and experimented with for this subject. Perhaps the best way of introducing the subject is to consider all the physical and chemical disturbances which could possibly be associated with a vessel—mechanical, acoustic, electrical, magnetic, etc., and the fundamental means of employing them. As regards the application of the disturbances, we may broadly distinguish between two methods:

(A) Those in which the disturbance is emitted by the vessel to be detected;
(B) Those in which it is emitted by the observing station or a separate source, and is reflected or intercepted by the vessel to be detected.

We may distinguish these methods by the terms, direct or homo-dynamic, and reaction or hetero-dynamic, respectively. The distinction is the same as between a source of light like a star or lamp and a body which is seen by reflection or by the shadow it casts.

We may further subdivide the latter or hetero-dynamic method into three classes:

(*a*) Simple reflection methods in which the object is detected in the presence of the primary impulse, e.g. ordinary vision.
(*b*) Echo methods in which the primary impulse is interrupted during the reception of the reflected disturbance.
(*c*) Shadow methods in which the impulse is intercepted by the object to be detected.

This simple classification, although apparently somewhat academic, is of the utmost value in guiding research. The bulk of physical disturbances diminish in intensity according to the square or cube of the distance from the source, as well as by absorption, which may in many cases be very rapid. If the disturbance emanates from the vessel to be detected, it diminishes in this manner, but if it emanates from the observing station and is reflected from a small object such as a ship, both the emitted and reflected disturbances are similarly dissipated and absorbed, so that the effect received diminishes as the fourth to sixth power of the distance, and the absorption is squared. On this account hetero-dynamic methods, although they may deal with much larger initial disturbances, have very little chance of being effective in comparison with homodynamic methods, unless the emitted energy can be concentrated into a nearly parallel beam. Anyone who considers how little can be seen with the strongest arc lamp if it is not enclosed in a projector, will realize the importance of this point, but in the early days of detection experiments all sorts of suggestions for detection by inductance bridges, even with wireless frequencies, were put forward without the smallest chance of success. The figures given for the absorption of electromagnetic waves in Appendix 3 appear to show that for all frequencies above 100 $\sim$ per second the attenuation even at a range of 100 metres is so large as to render all detection almost hopeless, while at sonic or radio frequencies even direct transmission is very minute. Fortunately, in the majority of cases the sources are not very deep, so that the waves soon escape into the air and can be detected above the surface. For this reason signalling even at wireless frequencies is not impracticable, but any devices depending upon submarine reflection or reaction cannot be expected to give satisfactory results at high frequencies.

Electrostatic effects of course cannot be looked for in the case of a body immersed in a conducting medium, but magneto-static effects are not interfered with, as the permeability of the water is approximately unity.

It need hardly be stated that optical methods if available would be by far the most valuable, as actual vision is the most conclusive evidence both of presence and of direction, but although sea water appears fairly transparent in thin layers, its absorption is too high to permit of objects being seen at any useful range, apart from the further difficulty of turbidity which exists in most shallow waters. In the clear water of the Mediterranean Sea the limit of visibility according to Professor Bragg is only about 200 ft., and it would not exceed probably 20 ft. in our home waters. The use of powerful illuminants also, even if of much value, is to be avoided as giving too much information. For these reasons scientific optical detection does not appear to have shown much prospect of utility, nor do thermal methods appear to have much applicability. A considerable amount of heat must obviously be emitted from a submarine, even when it is at rest, but radiation is of course rapidly absorbed. In very still water vertical convection currents would rise from the vessel and might easily be detected, but in moving water like the sea these must quickly be dissipated. Chemical action might possibly be detected at moderate ranges in still water, but, as with thermal effects, the moving water renders any possibility of direct chemical detection very remote.

It will be seen, therefore, that in spite of the number of phenomena theoretically available, and the possibility of applying them in various ways, the practical range of detecting devices is narrowed down to a comparatively few phenomena and modes of application, and it may be said that experience has very closely confirmed

the conclusions which were drawn from the above considerations. More accurate knowledge of the transmission of impulses in the sea may enable us to design our detecting devices more efficiently, but the general lines on which such development should proceed seem fairly clear.

Acoustic Devices.

The most simple device for acoustic detection is the elementary Broca tube consisting of a metal tube with a diaphragm at the bottom, which is dipped into the water. This device is practically equivalent to the familiar one of putting the ear to the ground or to a rod in contact with it. Improvements were made by the Americans in what were called C tubes, in which the diaphragms were replaced by rubber teats. Shortly after, microphones were introduced and various forms of hydrophones were devised.

Fig. 1 shows three forms of hydrophone which have proved of considerable service. In the first of these, marked A, a heavy circular metal case is provided with a diaphragm on one side, to the centre of which is attached an ordinary button granular microphone.

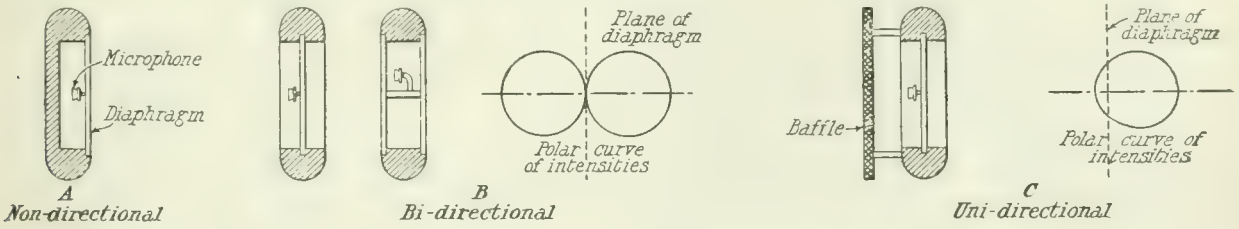


Fig. 1.—Types of hydrophones.

This is a fairly sensitive and effective hydrophone and has been in continuous service.

As mentioned above, the determination of direction is as important as the actual detection, and Fig. 1(B) is one of the best forms of directional hydrophone. It consists of a thin metal diaphragm about 4 in. diameter supported in a heavy lenticular-shaped ring so that the water is on both sides of it. At the centre of this diaphragm a simple granular microphone is fixed in a watertight capsule. When the sound waves strike the diaphragm nearly normally the hydrophone has its maximum sensitiveness, but when they are edge on, they act equally and oppositely on the two sides of the diaphragm, so that the effect is neutralized and no sound is heard. The positions of minima are very sharp and well defined.

The variation of intensity is approximately represented by the polar curve, which shows a minimum when either edge is towards the source. On this account this portable directional hydrophone is called bi-directional. Its sensitiveness is only about one-fourth of that of the non-directional form, but in spite of this it has proved of great value. A similar arrangement using two diaphragms coupled together had previously been employed by Mr. Sykes and Professor Morris, but its principle is the same.

By fitting one of these bi-directional hydrophones with what is termed a " baffle " plate, supported a few inches away from one face of the diaphragm as in Fig. 1(C) the sound is virtually shielded from that face, and a single maximum can be observed when the other face is turned to the source. This gives us a uni-directional hydrophone, but its directional properties are inferior to those of the unbaffled bi-directional instrument as the maximum is not very sharp and the minimum is also blurred. For this reason the best results are obtained by coupling a uni-directional and a bi-directional hydrophone on the same vertical axis, and to rotate them until silence is obtained on the latter combined with maximum intensity on the former instrument.

So far as fixed stations are concerned these hydrophones fulfil their promise very satisfactorily, but they are practically useless for the important case of listening from a moving ship, owing to the water noises produced by the motion. Very fair results have been obtained by enclosing the hydrophones in a water-filled streamline case attached to the hull of the ship in which the hydrophones can be rotated. But even then the noise of the observing ship's machinery is a serious disturbance, so that listening can only be done when the engines are stopped, or at least running dead slow.

Towed listening devices.—As listening under way is of prime importance, an immense amount of work has been done on towed devices, in which microphones are enclosed in rigid or flexible stream-line bodies, which are towed behind the ship. Considerable success has been obtained with some of these devices, but a difficulty then arises as regards direction. In some cases a small directional hydrophone can be employed inside the towed body, but it is frequently preferred to tow two or more hydrophones and to obtain directional indications either by " binaural " or " sum and difference " listening.

The binaural method developed largely in the United States depends upon the simple principle that if sound falls upon two receivers separated by a short distance, it reaches them at different times unless the source is in the median plane between them. If the two receivers communicate with the two ears, the source will appear to be on one side or other; but by rotating the bar carrying the receivers, the source appears to cross over behind the observer from one ear to the other, and this cross-over occurs when the bar is perpendicular to the direction of the source. This method has been found of the greatest value in the location of aeroplanes by employing two trumpets communicating by stethoscope tubes to the observer's ears, but it has been much less easy to apply to hydrophones, owing firstly to the difficulty of producing granular microphones which

are identical in acoustic properties, and secondly to the fact that it is often impossible to rotate the coupled hydrophones when attached to a ship or enclosed in towed bodies. The difficulty is enhanced also by the fact that the velocity of propagation, and hence the wave-length of a given sound, are nearly five times as great in water as in air, so that the distance between the hydrophones must be correspondingly increased.

If two ordinary microphones are fixed close together so as to be similarly affected by a source of sound, and are joined to the primaries of two ordinary telephone induction coils, as in Fig. 2, then if the secondaries of these coils are connected in series to a pair of receivers, the effect observed is either the sum or the difference of the effects of the two microphones according as the secondaries are assisting one another or are in opposition. If the two microphones behave exactly similarly, a loud sound should be heard when they are assisting; and no sound at all should be observed when they are opposing; but with ordinary carbon microphones it

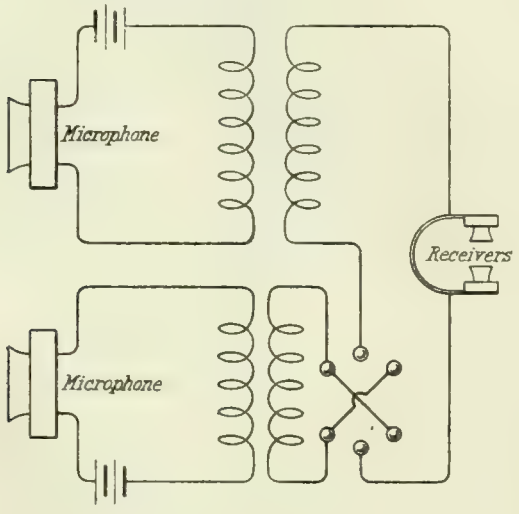


FIG. 2.—"Sum and difference" method.

frequently happens that hardly any difference is noticeable, owing to different phase relations in the two microphones. By replacing the ordinary mica diaphragms by indiarubber the selective properties of the microphones are much reduced and better balance can be obtained. In this way, and by enclosing the microphones in rubber blocks, fairly perfect pairing can be obtained, which is essential if correct binaural listening is required.

As above mentioned, however, the rotation of the bar carrying the microphone is a troublesome matter, and to obviate this, various forms of binaural compensator have been employed which enable directions to be obtained without rotation of the microphones. These compensators depend on the principle of introducing variable lengths of air path between the receivers and the observer's ears. If the sound reaches both microphones in the same phase, i.e. from a point in the median plane between them, and each microphone is connected to a receiver at the corresponding ear of the observer there will be binaural balance; but if the source is on one or other side of this plane there will be a difference of time between the arrival of sound at the two microphones, which can be compensated by a different length of air path between the receivers and the ears. Fig. 3 shows diagrammatically a simple form of straight sliding compensator, in which the receivers are fixed at opposite ends of a long straight tube, the centre portion of which can slide in the end portions so as to obtain the required difference of path. A more convenient form of compensator is made by the Automatic Telephone Company, and is similar in principle to the original American instrument. Two circular plates are arranged to revolve smoothly over one another, and have grooves cut in their faces, forming the air paths. The sound from the receivers is introduced into these grooves and taken from them to the ear by rubber tubes, and by revolving one of the discs the length of air path on one side is lengthened, and on the other side shortened, so that by turning the compensator the same effect is produced as by rotating the microphones.

Instead of binauralling, some observers prefer to work directly on the "sum and difference" principle above

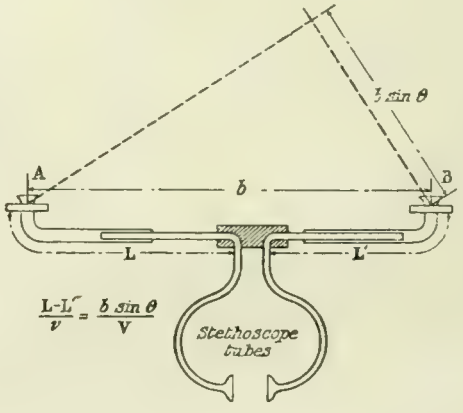


FIG. 3.—Binaural method with rectilinear compensator.

described. If the source is in the median plane between the microphones, and they are properly paired, there will be no sound with the "difference" connection; but if it is to one or other side of this plane, there will be a certain amount of sound which can be balanced out either by swinging the microphone or by introducing the compensator as above. Professor Spearman has introduced a reversing stopcock device for interchanging the stethoscope listening-tubes to the ears, which increases the accuracy of binaural listening.

Lastly dealing with directional combinations, two or more simple hydrophones are towed simultaneously so as to have fixed base lines, and the binaural or the "sum and difference" principle is employed with them. Two such hydrophones can be towed one behind the other as in Fig. 4 (*a*), but in that case there will be no indication on which side the source is; the time difference is evidently the same for any point on a circle surrounding the axis, or for the points P and Q in the figure. By towing two hydrophones abreast with

a spreader as in (*b*) this ambiguity disappears, but it is then uncertain as to whether the source is ahead or astern. If three hydrophones are used as in (*c*) this ambiguity is eliminated, as binauralling can be conducted on any pair. In Fig. 4 (*d*) we have the towed body devised by Messrs. Redfern and Dobie of the Lancashire Group in which three hydrophones are mounted on a board with streamed edges.

The above is only an outline of the immense amount of work which had been done on towed listening devices, to say nothing of the special cables which have been constructed to take the considerable strains involved. For this purpose cab-tyred cables with central steel cores have been largely used, and the various cable manufacturers have rendered great service in their design and construction.

Inboard listening.—Although the towed devices have met with a certain measure of success, they are trouble-

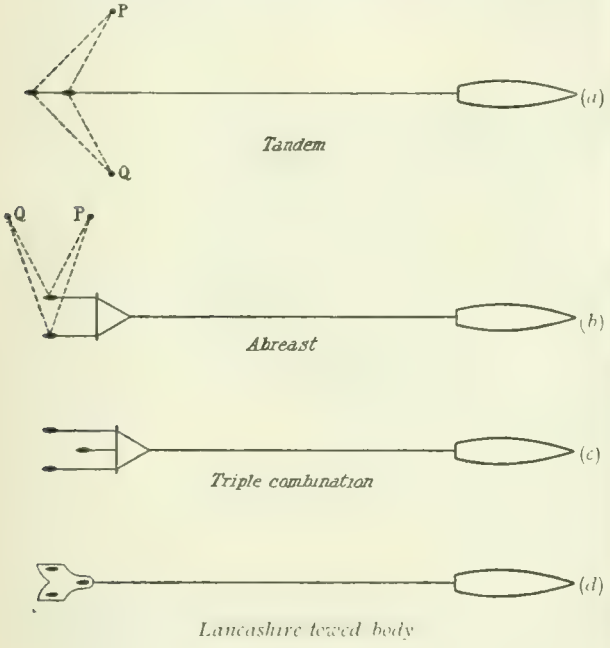


Fig. 4.—Towing schemes for hydrophones.

some to handle, and the modern tendency is in favour of the development of listening apparatus for use on board ship. Although this is a difficult problem, on account of water and ship noises, there is a valuable principle which greatly assists its solution. This may be called the principle of acoustic integration, apparently first put forward by Professor A. W. Porter, which points to the employment of large flat surfaces for reception.

Many important applications of this principle have been made both in the United States and in this country, and considerable success has been obtained with the devices based on it. The chief objection to it is that it is obviously impracticable to swing a large receiver on board ship to receive from various directions; but this difficulty has been to a large extent overcome by introducing a variable phase difference into the microphone or other receivers attached to different parts of the diaphragm, thus enabling a maximum sensitiveness to be obtained for various directions of the source. Professors Mason and Pierce have produced valuable inboard listening devices in this way, and the author has devised a "magnaphone" or large magnetophone which applies the principle in the simplest possible manner.

Before leaving this subject two interesting devices employing an analogous principle may be described. The first of these is the Walser gear invented by Lieut. Walser of the French Navy. Instead of using a large plane receiving-surface he employs a pair of "blisters" or spherical dilatations on the two sides of the hull. Each of these blisters is about 3 ft. 6 in. diameter and is provided with a large number of thin circular diaphragms, so that the arrangement looks like the compound eye of an insect. When sound waves fall on this blister the vibrations of the diaphragms are communicated to the interior air and come to an approximate focus as in the case of a lens or rather of a "zone plate." A conical trumpet placed at this focus and provided with

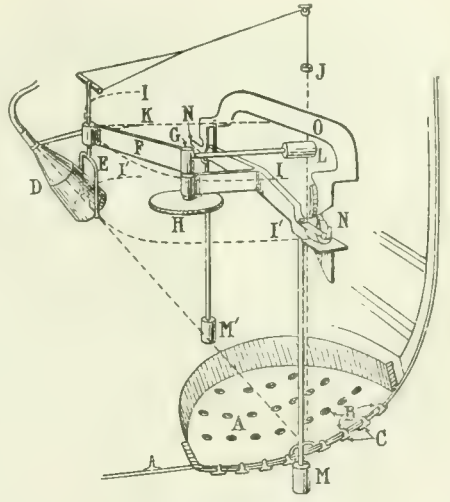


Fig. 5.—Internal mechanism of Walser gear.

A Blister.
B, C Diaphragms.
D Collecting trumpet.
E—N Rotating gear.

a rubber tube and ear piece is all that is required for listening. As the direction of the source changes, the position of the focus revolves round the centre of curvature of the blister, and by mounting the trumpets on suitable rotating gear, the observer is able to locate the source by first observing whether the sound is louder on the port or starboard side and then rotating the trumpets till a maximum is obtained. Fig. 5 shows the internal mechanism of a Walser cabin.

A second device of great theoretical interest is the hydrogen or H tube of Mr. H. W. Hilliar. The velocity of sound in hydrogen and in water is very nearly equal. If, therefore, sound arrives at the end of a long tube at practically the same speed as it does in the water outside, and if the tube is turned towards the source, the sound entering at every part of it reaches a receiver or listening tube at the end in the same phase. This may be called the principle of longitudinal integration,

as distinguished from that of transverse integration previously described, and it has the advantage that the whole of the sound collected from the entire surface of the tube is concentrated on a single receiver. If the source is not in line with the axis of the tube the axial velocities are not the same, and partial cancellation results, so that the device is directional. At ordinary temperatures, the velocity of sound in hydrogen is somewhat less than that in water, but by steam heating the hydrogen the velocities can be made practically exactly equal, and the device is found to have fairly definite directional properties.

There can be little doubt that there is a great future for inboard listening devices, especially if improvements are made in reducing engine noises in the ship, but the great size of the integrating devices renders experimental development slow. In the meantime good work has been done in the application of inboard magnetophones with devices for eliminating water and other noises on the interference principle. Magnetophones are inferior to microphones in actual sensitiveness, but they have the advantage over them of having no grating or crepitational noises, so that they will stand considerable amplification, and they are easy to pair for binauralling.

Fig. 6 shows Mr. B. S. Smith's form of "air drive" magnetophone, which consists simply of an ordinary Brown reed telephone-receiver mounted behind a diaphragm fixed on a heavy metal ring which is attached to the ship's side with the intervention of a rubber sound-insulating ring. The vibrations of the diaphragm are communicated to the reed through the air in the interior, causing it to vibrate and to act as a magnetophone. By employing four or more of these devices at different parts of the hull, approximate directions can be determined, which can be rendered more exact by binauralling.

Burgess interference tubes.—A very useful device in connection with listening arrangements of every kind, and which assists the reduction of disturbances with non-integrating hydrophones, is that introduced by Mr. J. A. Burgess. The sound from the receivers is led into an arrangement of tubes like a trombone so that it divides into two paths in parallel before re-uniting. If the difference of the two paths is half a wave-length for a particular frequency, that sound will be eliminated, and by employing a number of pairs of tubes a number of frequencies can be blotted out while other sounds can still be heard. In this way the disturbances due to water noises, etc., may be greatly reduced, and the frequencies of different sounds determined.

An improved form of this arrangement has been devised by Mr. B. S. Smith on the lines of the American compensator, the required differences of path being obtained by a number of rotating discs.

Echo methods.—All the devices so far described are for direct listening, i.e. they depend upon the sound emitted by the submarine. When the latter is stationary or drifting, however, they are of course useless, and acoustic methods can only be employed if the submarine either reflects or intercepts sound from another source. Reflection or echo methods are naturally the more convenient as in this case the source

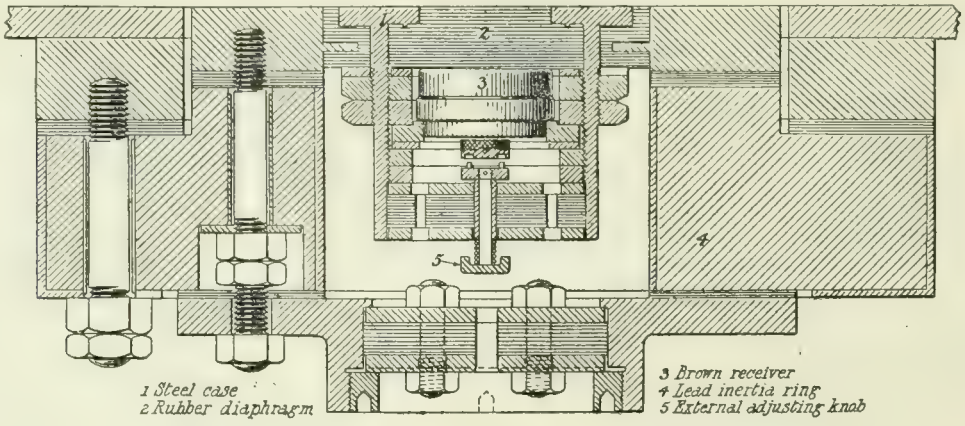


FIG. 6.—Air-drive magnetophone.

of sound can be on the observing ship, and it is obvious that as the object to be detected is small compared with any useful range the source must be of considerable intensity. A large number of devices have been constructed for producing powerful sounds under water, such as submarine bells and tappers, oscillators operated by alternating current of sonic frequency, submarine syrens and steam jets. Among those which may be mentioned are the Wrightson syren in which a stream of water of about 30 gallons per minute is employed with a motor rotating a cup perforated with holes, as in the ordinary syren. This is a very powerful device, but needs a rather large pump. The Fessenden oscillator consists of a diaphragm which can be attached to the side of a ship and to which is fixed either a soft-iron armature attracted by an electromagnet excited by the alternating current, or a coil traversed by an alternating current and moving in the gap of a powerful electromagnet.

By means of these powerful acoustic transmitters, not only is sound signalling possible at long distances but echoes have been obtained at considerable range. For open deep-sea work they may be of considerable

value, where the object to be detected is far away from other ships or rocks or reflecting surfaces, but for working in shallow confined areas or in the presence of a large amount of shipping they may lead to great confusion, and it is therefore desirable to be able to concentrate the emitted disturbance into a narrow beam and to rotate it into any direction required. As has been seen, this can be done by the principle of integration, and most interesting and powerful methods of location have been developed on these lines, which enable the direction and approximate range of a submerged object to be determined from a ship at full speed.

High-frequency acoustic detection.—This is probably the most powerful method of detection yet devised, and arose out of the "Titanic" disaster in 1912, when Mr. Lewis Richardson took out two patents for detecting obstacles by echo either in air or water, by employing a beam of "sound" of frequency from 5,000 to 100,000 periods per second. Apart from their special application to submarine detection, these echo methods promise to be of the greatest value for the detection of rocks and other ships and probably of icebergs, and also for sounding operations. Their application will be referred to later.

The foregoing account gives an outline only of the immense amount of work which has been done on acoustic detection. On account of the sensitiveness of acoustic devices and the low absorption of sound waves in the sea, the development of acoustic methods must always hold a great place, and they most certainly were of great value when they were first brought to service state. Had the submarine always remained as noisy as it was originally, no other devices would have been needed. The modern improvements in submarine machinery and tactics, however, have very greatly reduced the possibility of detection by acoustic means. By running slow on motors or by drifting with the tides and currents, submarines have been able to preserve a certain amount of mobility with almost complete silence, apart from their ability to remain stationary either on the bottom or floating; and under these circumstances direct acoustic detection apart from echo methods becomes impossible. This does not altogether detract from the value of acoustic methods, however, as the mere fact of the existence of listening gear seriously hampers the rapid movement of submarines by forcing them to go almost dead slow. Acoustic gear may in this sense be likened to a police force which may seriously limit the activities of criminals without convicting or even detecting them, and in this respect its value must always be recognized. Nevertheless it is imperative to have other methods of detecting the silent submarine, but this is a matter of the greatest difficulty, as indicated at the outset.

Electromagnetic Methods.

These methods are usually based on the Hughes induction balance, which was seized on by a number of inventors as the most attractive principle for detection. Unfortunately this impression is illusory, as has already been indicated in the introduction. The method is essentially heterodynamic, so that we have to deal with the attenuation of the magnetic field from the coils and again with that of the induced field from the object to be detected. The magnetic field from a coil of small dimensions compared with the range, diminishes as the cube of the distance, and the absorption due to the conductivity of the water is very large at all but the lowest frequencies. As the reaction due to the obstacle also diminishes as the cube of the distance and is similarly affected by absorption, its reactive effect on the coils diminishes as the sixth power of the distance, and the absorption is squared, so that although the sensitiveness may be remarkably great when the object is close to the coils, it practically vanishes at a very moderate range. From the point of view of measurement, a moderately high frequency is desirable, in order that the inductive effects should be large in comparison with the resistance of the coils; but absorption absolutely precludes this. In consequence the practical possibilities of this method seem theoretically to be very small, and all experience has confirmed this.

Other Methods of Detection.

Although the above by no means exhausts the list of methods which have been experimented with or employed, it covers the bulk of useful and promising devices. Certain optical methods have been employed with some success, but do not warrant description. Thermal devices as above mentioned do not seem promising.

In addition to detection devices much valuable work has been done as regards secret signalling which may be a valuable aid to detection, but this cannot be gone into.

For obvious reasons nothing can be said about the tactical employment of these devices, which, however, has engaged a considerable amount of attention.

Since the Armistice this detectional work has gone on with unabated zeal, but it has been realized that a greater knowledge of the scientific principles involved is of prime importance for future development, and this will be dealt with in the last section. In view, however, of the difficulty of the problem, the small amount of knowledge available and the exigencies of war-time work, the record is one of which our country and our Allies may well be proud.

II. DEFENCE AND DESTRUCTION.

Defensive and destructive methods are of no less importance than detection, and form a most fascinating branch of the subject with which the lecturer has more especially been concerned. The bulk of the applications to submarine mining, etc., must, however, be kept secret.

A most valuable device which has become fairly well known and which has probably done more for the protection of vessels against mines than all other inventions put together is the paravane, which was invented by Commander C. D. Burney, R.N. This consists of a torpedo-shaped body towed from the vessel to be protected, and is provided with vanes so that it keeps outwards and below the ship. When the towing cable meets the mooring rope of a mine it forces it away from the ship, and the rope slips into jaws

which cut it through. Explosive paravanes have also been made for protection against submarines.

Apart from the internal mechanism of mines, there are the problems associated with laying them in water of different depths and of their motion in tides and currents, as well as with their destructive effect. These

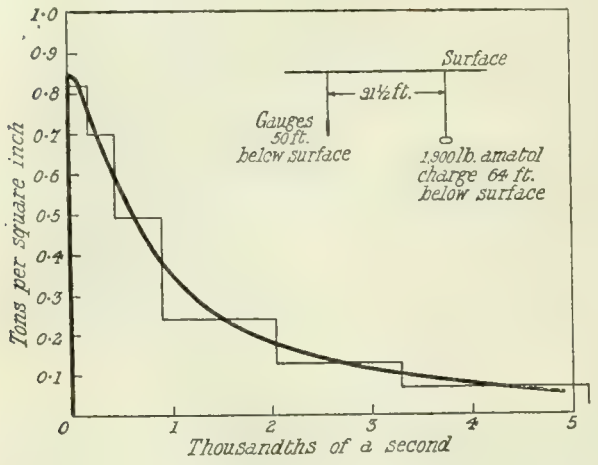

Surface
31½ ft.
Gauges 50 ft. below surface
1,900 lb. amatol charge 64 ft. below surface
Tons per square inch
Thousandths of a second

FIG. 7.—Time-pressure curve for 1,900 lb. amatol charge.

problems are of the most intricate character and have engaged a very large amount of attention. One matter which may be referred to here is the determination of the pressures developed in the water by explosive charges of different magnitudes. This has been investigated by two independent methods.

In the first of these, which has been most ably employed by Mr. H. W. Hilliar, the pressure is measured

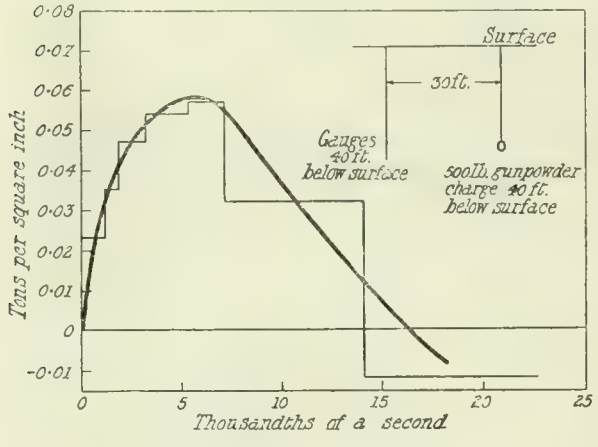

Surface
30 ft.
Gauges 40 ft. below surface
500 lb. gunpowder charge 40 ft. below surface
Tons per square inch
Thousandths of a second

FIG. 8.—Time-pressure curve for 500 lb. gunpowder charge.

by the compression of small copper gauges similar to those used in ordnance trials. A number of these gauges are enclosed in cylindrical holes in steel blocks, with steel plungers of different lengths. When the explosion wave reaches the block, the steel plungers are driven in and compress the gauges, but the time for the plunger to reach the block depends on its mass and length of travel and hence the variation of pressure with time can be determined. Fig. 7* shows one of these time-pressure curves taken at a distance from a 1,900 lb. amatol charge at a distance of 92½ ft. and at a depth of 64 ft., the gauges being 50 ft. below the surface. The pressure rises to nearly a ton per square inch in about 10,000th of a second and falls to about a tenth of this value in 0·004 second. With a gunpowder charge (Fig. 8) the rise of pressure is much slower and it is longer maintained, though of much smaller intensity.

It has been found from these experiments that these high-pressure explosion waves travel with the same velocity as sound in the water (about 4,900 ft. per second), that the explosive charge required to produce a given pressure is proportional to the cube of the

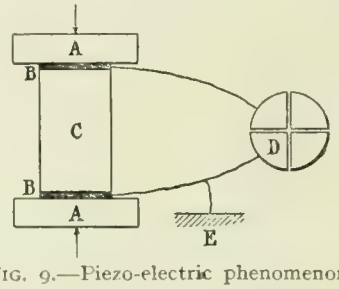


FIG. 9.—Piezo-electric phenomenon.

distance, and that the pressure is sustained for a time proportional to the distance.

The second method of making such investigations is of a most interesting scientific character, and gives a continuous record of the variation of pressure. It was suggested by Professor Sir J. J. Thomson and developed by Mr. D. A. Keys at Shandon, and depends on the piezo-electric phenomenon so fully studied by the late Professor Curie. If a crystal such as quartz or tourmaline is subjected to pressure along its optic axis (Fig. 9) it becomes electrically charged on its surfaces, and as the elasticity of such crystals is very high this charge is developed practically instantaneously, and is proportional to the total force on the crystal independently of its dimensions. By mounting plates of quartz or tourmaline in contact with a rigid metal backing and facing them with an insulated tinfoil sheet, the charge developed can be communicated to

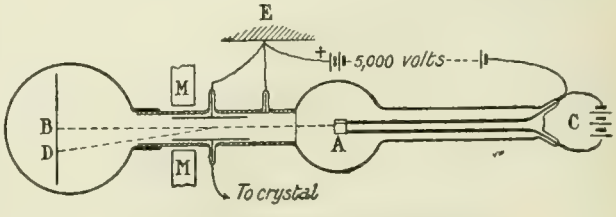


FIG. 10.—Cathode-ray oscillograph.

an electrometer so that the arrangement makes a very convenient pressure indicator.

For the purpose of recording very rapidly-varying pressures a cathode-ray oscillograph is used. The form hitherto employed was lent by the Cavendish Laboratory and is shown in Fig. 10. A stream of electrons is emitted

* Figs. 7 to 11 have been taken from a paper by Professor J. C. McLennan, F.R.S., entitled "Science in its Application to Marine Problems," read before the Northern Society of Shipbuilders.

by an 8-volt tungsten filament in a bulb, and passes through a pinhole aperture in a copper anode, between which and the filament a constant potential difference of about 4,000 volts is maintained by a high-voltage generator. The fine cathode-ray pencil thus produced passes first between the poles of a laminated electromagnet, and then between two long brass plates which are respectively connected to the tinfoil coating of the crystal receiver and to earth. After passing these plates the cathode-ray pencil passes into a camera in which a fluorescent screen is fixed. The whole apparatus is exhausted to an X-ray vacuum by means of Gaede and auxiliary pumps. When the filament is glowing and the high potential difference is applied, a bright spot is seen on the fluorescent screen. On exciting the electromagnet this spot moves transversely across the screen in a direction perpendicular to the magnetic field, and on applying a small potential difference between the two brass plates, it moves in a direction at right angles to this. For the purpose of obtaining the records the electromagnet is excited by an alternating

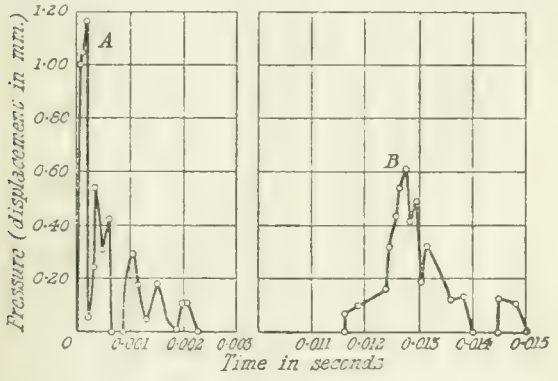


FIG. 11.—Explosion-pressure record from cathode-ray oscillograph.

A Original shock. B Reflected impulse.

current of about 80 ∼ per second, causing the spot to move over the screen in a simple harmonic manner, each traverse taking 1/160th second. The crystal receiver is suspended in the water with its face turned towards the explosive charge, and is connected through a highly insulated low-capacity cable to the brass electrode plate of the oscillograph. When the explosion occurs the beam is deviated laterally by an amount proportional to the pressure at each instant and a time-pressure curve is traced out on the screen. This can be recorded by lowering a photographic plate in front of the screen, by means of a cord and pulley turned through an airtight gland.

Fig. 11 is a record obtained by this device after reducing the time intervals to a uniform scale. It shows considerable irregularities, possibly due to reverberations in the water and to non-simultaneous firing of different portions of the charge, but its general form corresponds fairly well to the curves obtained by Mr. Hilliar. Absolute pressures were not obtained, but arrangements have been made for calibrating the device by applying known pressures.

An interesting point shown in curve B is that the reflection of the pressure wave by the bottom of the sea produces a second impulse of magnitude comparable with the direct impulse. It has also been found both from Mr. Hilliar's and from Mr. Keys's experiments that surface reflections produce tension waves of magnitudes sometimes exceeding the static pressure, indicating that the water may actually sustain a considerable tension for short intervals.

The practical importance of these experiments is very great, as it enables the destructive radius of various mines to be determined and the designs of mines and mine-fields to be conducted on a scientific basis. On this account, and for many other investigations, a new form of cathode-ray oscillograph has been designed at Shandon which is portable and self contained, and in which a roll-film camera is employed, actuated from outside by electromagnetic mechanism. Arrangements have also been made for attaining a uniform time scale so that the record needs no after-treatment.

A number of special instruments have also been devised for studying and recording the motions of mines in tideways, etc.

III. NAVIGATIONAL APPLICATIONS.

One of the most fortunate circumstances resulting from the large amount of research undertaken for war purposes is that the majority of the information and devices so evolved have the most important application to peace-time navigation.

Although ships and ordinary methods of navigation had already been developed before the war to the extent of rendering maritime transit remarkably safe and almost independent of storms, fog has always been a serious and dangerous obstacle, causing great delay, apart from accidents, while the dangers of icebergs, derelicts and uncharted rocks need no insisting on. The "Titanic" disaster in 1912 brought these dangers vividly before the public, and several suggestions were made soon after for guarding against them, some of which as mentioned above have been of value in the anti-submarine campaign.

The question of safe and rapid navigation in foggy weather is a matter of great Imperial importance, as the Canadian service is often seriously delayed by fog off the Banks and at Halifax and the St. Lawrence River, so that passengers and goods often travel by the American routes for greater certainty.

The three chief desiderata for the safety and regularity of navigation appear to be as follows, in the order of their importance:

(1) Ability to find and enter a harbour in foggy weather.
(2) Location of position in sea during fogs.
(3) Detection and location of ships and obstacles in darkness and fog.

These three requirements can now respectively be met to a considerable extent by the following devices:—

(*a*) Leader gear.
(*b*) Sound ranging and directional wireless.
(*c*) Echo detection.

Fortunately it is possible to deal with these matters in greater detail.

Leader Gear.

This device which promises soon to come into considerable practical use, consists of laying down a cable on the bottom along the track which it is desired to follow, and to supply it with alternating current of either sonic or infra-sonic frequency. By the use of suitable coils or electrodes attached to the ship the electromagnetic induction or the return currents in the water

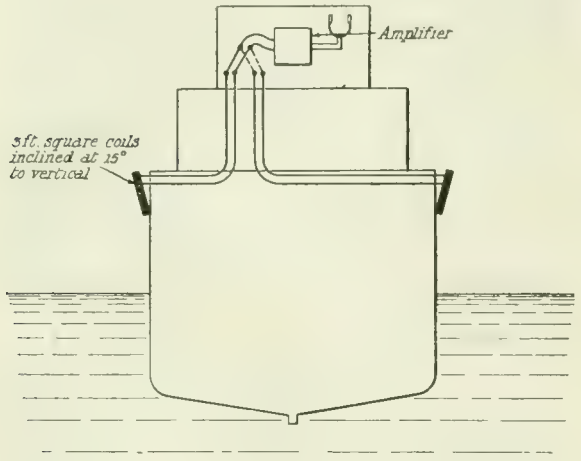


Fig. 12.—Aural leader gear.

can be made to give signals in telephones or other devices by which the course of the cable may be followed.

Attempts were first made in this direction in the St. Lawrence River by Professor R. S. Owen as early as 1903, but were only partially successful, chiefly because amplifiers were not then available. During the war the idea was revived by Captain Manson, employing search coils and amplifiers, and successful results were immediately obtained. Two coils of about

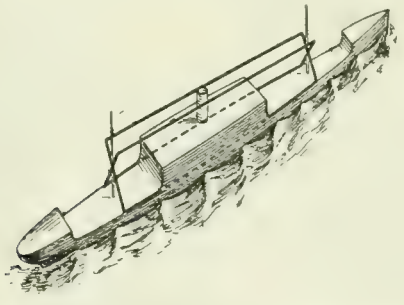


Fig. 13.—Ship coils for visual leader gear.

4 ft. square are fixed on the sides of the ship a short distance away from the ironwork, and are connected to a change-over switch and three-valve amplifier and telephones. The cable is supplied with alternating current of a frequency of about 500 ∼ per second, and this current is cut up into signals by an automatic interrupter. Steering is effected by listening on the two coils alternately, the signals being stronger on the side of the ship nearer to the cable. The difference in intensity is apparently due to the screening action of the iron hull, and varies with the size of the ship, but it is usually possible to find positions of the coils which give good indications. Fig. 12 is a diagram of the arrangements.

In order to avoid the necessity for listening to telephones, the author has attempted the somewhat bold step of employing tuned alternating relays to operate lamps on the navigating bridge of the ship, and thus to give continuous visual indications. For this purpose two inclined coils of a few turns are fixed in the rigging as shown in Fig. 13. If the lines of magnetic force are in circles round the cable as generally supposed (Fig. 14), the electromotive forces induced in the two coils should be equal when the ship is vertically over the cable, but when it is on one or other side the

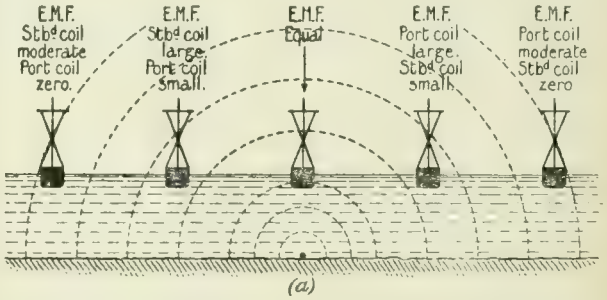

E.M.F. Stbd coil moderate Port coil zero.
E.M.F. Stbd coil large. Port coil small.
E.M.F. Equal
E.M.F. Port coil large. Stbd coil small.
E.M.F. Port coil moderate Stbd coil zero
(a)

Fig. 14 (*a*). –Ordinary circular field distribution showing E.M.F.'s in sloping visual leader-gear coils.

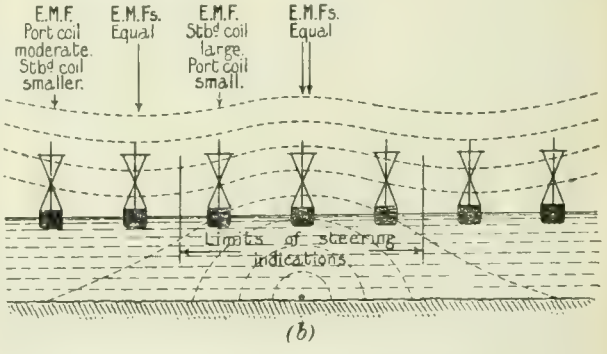


Fig. 14 (*b*).—Field distribution distorted by sea water, showing E.M.F.'s in visual leader-gear coils.

E.M.F. in the coil pointing more nearly towards the cable will be the higher. At a certain lateral distance from the cable the plane of one of the coils will be tangential to the lines of force, and will consequently have no E.M.F. induced in it.

Fig. 15 shows the construction of the alternating-current relays employed in conjunction with this device. It is on the same principle as the author's vibration galvanometer, in which a pivoted or suspended iron needle vibrates in the field of a horseshoe magnet and can be tuned by varying the intensity of the magnetic field. This needle is enclosed in a simple coil carrying the alternating current, and is provided with an arm carrying a rounded platinum end which makes contact with two fine tangential platinum wires when it vibrates. As the contact is intermittent, it is found desirable to convert it into a continuous contact by the simple

device of passing the local current from the vibrating contacts through the coil of an ordinary heavily-damped moving-coil relay, the contact arm of which slides between two sets of parallel platinum-wire brushes so that when the coil is deflected, and oscillates owing to the intermittency of the current, it maintains a continuous rubbing contact against the brushes. The two relays are combined in a single magnet as shown, and the tuning is very simply effected by traversing the whole of the alternating-current system along the axis of the magnet by means of a screw, so as to be in a stronger or weaker magnetic field.

It is fairly easy to set the contacts of this relay to work with a power consumption of 0·01 microwatt or less, which is amply sufficient to enable it to switch on a glow lamp at $\frac{3}{4}$ mile from a cable carrying only

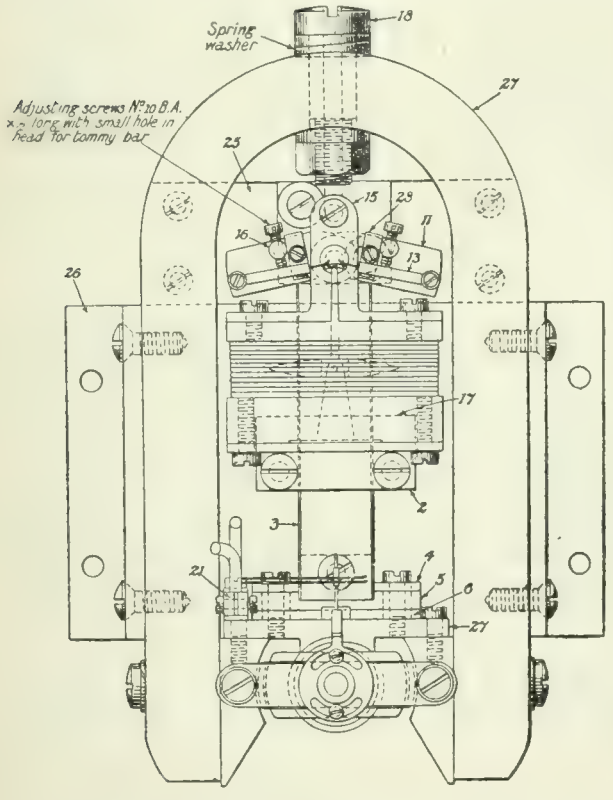


FIG. 15.—Alternating-current relay.

5 amperes of alternating current in a depth of water of 20 fathoms.

A relay on a similar principle was devised by Mr. Sidney Evershed as far back as 1896, but was unfortunately unknown to the lecturer at the time. Mr. Evershed went much further and designed a vibrating-wire relay which operated with only 0·0001 microwatt, but it is desirable to have a fairly robust instrument for use on shipboard and it is necessary that the relay should be fairly definitely metrical in its operation for the present purpose.

The tuning of this relay is fairly sharp, as is shown by the curves in Fig. 16, and this requires the frequency of the current supplied to the cable to be maintained constant within about $\frac{1}{4}$ per cent of its nominal frequency, but this has the attendant advantage that different cables can be used with different frequencies without mutual interference. For example, in wide estuaries like the Mersey and the Clyde where there is a considerable amount of cross traffic, it is easily possible for the main and cross routes to be worked quite independently by using different frequencies. The curves shown are for the three relays of one of the indicating sets, and the sharper curves are for a previous

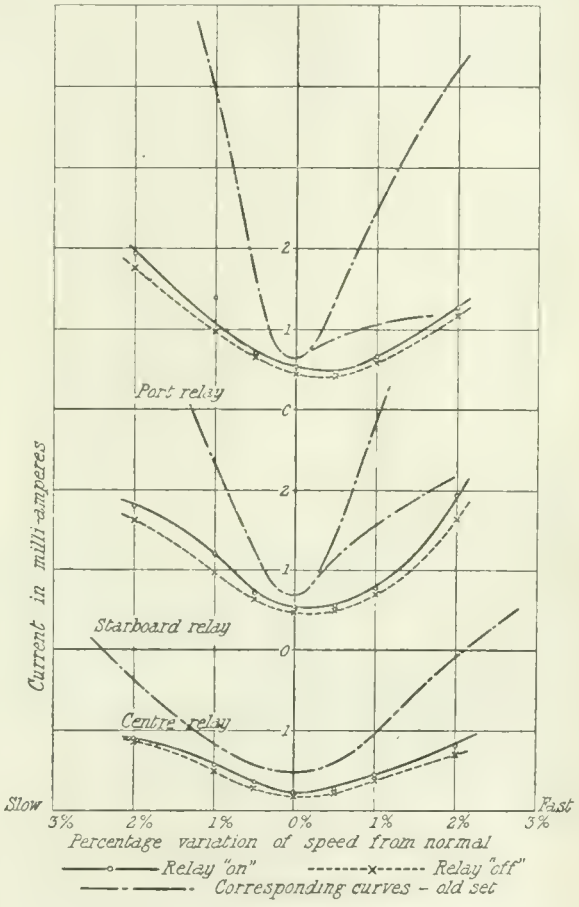


FIG. 16.—Resonance curves for alternating-current relays: variation of sensitiveness with frequency. Triple set in iron box with large tremblers.

set with smaller movement, in which the tuning was inconveniently sharp.

In order to keep absorption and distortion of the electromagnetic field as small as possible, low frequencies of between 10 and 20 ∼ per second are used with this device, and this makes the presence of the cable almost undetectable unless the frequency is known.

Unfortunately, however, when this device was first experimented with it was found practically impossible to get definite port and starboard indications for steering purposes, and it was therefore found necessary to investigate the distribution of the magnetic field, by observing the E.M.F.'s induced in the two inclined leader gear coils, with the result of finding that

even at these low frequencies it was greatly distorted. Fig. 17 shows the distribution determined in the case of a cable in about 100 ft. depth of water with a frequency of ·15 ∾ per second. It will be seen that at the points marked A and B where the lines of force should be nearly vertical according to the ordinary theory, they are actually horizontal, so that instead of one relay being out of operation both are equally affected, and there can be no port or starboard indication. At greater distances from the cable the magnetic field actually bends upwards again, so that the indications are reversed. In order to avoid ambiguity, therefore, it is necessary to limit the sensitiveness of the relays so that they only operate with an E.M.F. above its value at the points of inflection and the steering indications must be limited to a range of 60–70 yards on either side of the cable as shown in the lower part of Fig. 14, which is ample, however, for navigating a narrow channel. In order to give even sharper indication of the position of the cable, a pointer indicator on the ohmmeter principle may be used, which is actuated by the contacts of the alternating-current relays. When the two relays are vibrating equally, the average value of the intermittent current from the contacts of each is the same, and the needle points directly down to the cable, but if the ship is on one side and the electromotive forces in the coil are therefore unequal, the average duration of contact in one relay is greater than in the other and the pointer goes over to the side on which the cable lies.

A triple alternating-current relay set is used, two of the relays actuating the port and starboard red and green lamps, while the centre relay is set to maximum sensitiveness and switches on a white "approach" lamp, indicating the first approach to the cable at a distance of $\frac{1}{2}$ to $\frac{3}{4}$ mile. After this lamp lights, the ship keeps on the same course until the red and green lights glow and then steers along the cable by the latter.

In the early experiments with this device the frequency was hand-regulated by means of a simple stroboscopic device, in which a Neon tube illuminated from the contact of a standard tuning-fork was used in connection with a geometrical disc on the rotary-converter shaft. In order to avoid the necessity for hand regulation a simple automatic speed controller has been devised. A small magneto generator of the type used for electrical tachometers is attached to the shaft of the alternator and its E.M.F. is balanced against a few secondary cells through a sensitive moving-coil relay. Exact balance of E.M.F. for the speed required is obtained either by rotating the brushes of the magneto by screw gear or by shunting the generator with a variable resistance. When the speed rises or falls the relay switches on one or other of two pairs of electromagnets actuating a rocking arm which actuates a reversing switch in the armature circuit of a small motor, causing it to run in one or other direction and to traverse the contact of a rheostat in the field circuit of the main rotary converter or driving motor. When the speed is correct and the rocking arm is horizontal the armature of the small motor is short-circuited by two springs so that it pulls up suddenly and prevents over-running, while if the supply voltage varies so greatly as to traverse the contact near to its limits, an electric bell is rung which calls the attention of the engineer to the need for adjustment. This device appears to

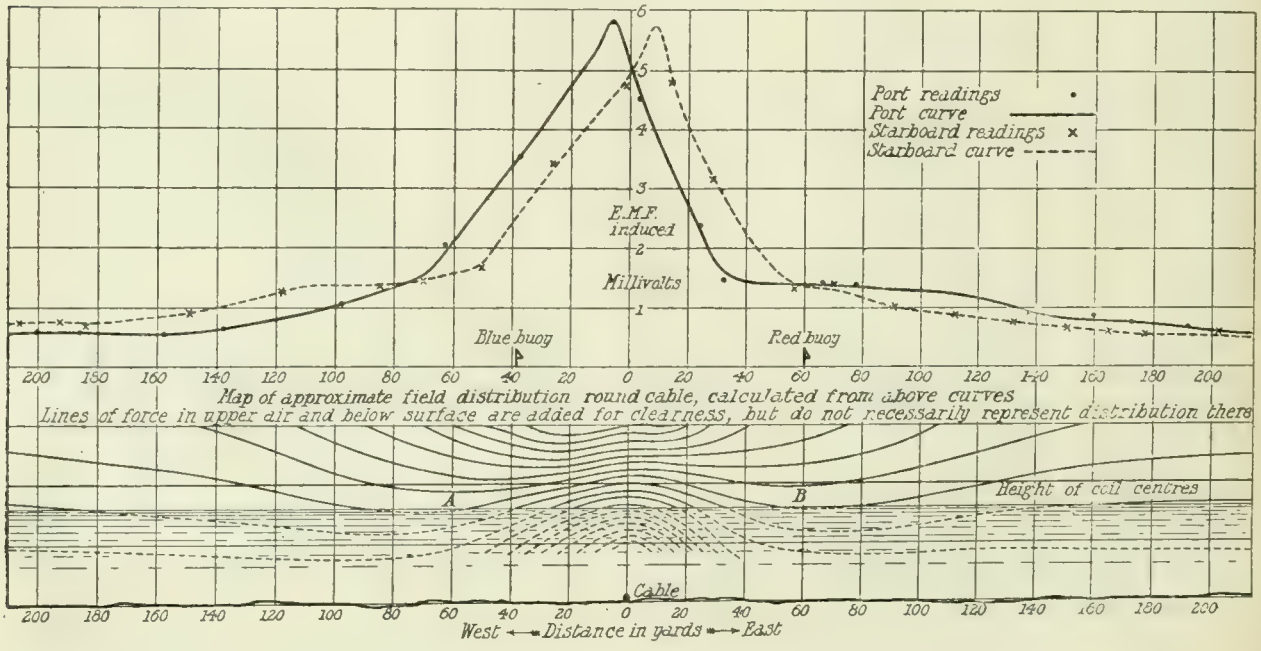

Port readings
Port curve
Starboard readings
Starboard curve
E.M.F. induced
Millivolts
Blue buoy
Red buoy
Map of approximate field distribution round cable, calculated from above curves
Lines of force in upper air and below surface are added for clearness, but do not necessarily represent distribution there
A
B
Height of coil centres
Cable
West ← → Distance in yards ← → East

FIG. 17.—Visual leader gear.

E.M.F. induced in ships' coils with spreaders 20 ft. long. Vibration galvanometer 500 in series. Sensitiveness, 3·43 cm. per millivolt. Vessel crossing west to east, heading south. Current in cable 6 amps. Frequency, 15 ∾ per sec. Depth, 16–17 fathoms at cable.

control the frequency to within 0·1 or 0·2 per cent of its nominal value, which is amply sufficient for the leader gear.

It has been found easily possible to operate both the aural and visual systems of indication simultaneously on the same ship and with the same cable. For this purpose the cable is supplied from a high-frequency and a low-frequency alternator in series as shown in Fig. 18. The inductance of the low-frequency machine is sufficient to choke down the high-frequency current almost completely, but by connecting a 20-mfd. condenser in series with the automatic signalling key across the armature of this low-frequency machine, the interrupted high-frequency supply can be maintained without affecting the low-frequency supply. It is therefore possible for ships to use either the aural or the visual indicating systems with the same cable, or to combine both indicating arrangements on the same ship without mutual interference.

Leader gear promises shortly to be adopted for practical navigation, as a cable about 18 miles long has been laid down at Portsmouth, and a notice appeared in the *Naval and Military Record* of 10th March last that this cable is available for use by vessels fitted with the necessary receiving apparatus.

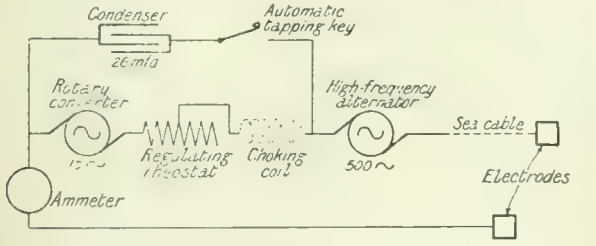


FIG. 18.—Connections for combined aural and visual leader gear.

Acoustic methods using submarine bells for guiding ships have been in use for a considerable time, and have been developed by the Submarine Signal Company in the United States. They may be employed with great utility in conjunction with leader gear by having a sounding device at the end of the leader cable, enabling the ship to steer towards the end of the cable from a distance of 10 miles or more.

SOUND RANGING.

Although leader gear promises to be of great service for guiding ships into and along harbours, it is obviously impossible to apply it generally for navigation in the open sea. It is therefore desirable to have some means whereby a ship in a fog can easily ascertain or be given its position, and thus avoid dangers, or be guided towards a leader cable. This may be done by directional wireless, which need not be dealt with in detail here as it has been covered by recent papers before the Institution. By obtaining bearings in this way with reference to two known fixed stations emitting continuous signals, the ship can obtain her position without other communication, and this device would be perfect if it were not that the ship's hull may disturb directional indications and give false bearings. This trouble may be circumvented by experimentally determining the deviations, but it may be a source of uncertainty.

Another method which requires no observations on board ship is by means of submarine sound ranging. If a sudden impulse such as an explosion is produced at a given point the disturbance spreads out in all directions and can be received on three or more fixed hydrophones or shock receivers. If there are only three receivers and the explosion takes place at the centre of a circle passing through them, the impulse should reach all the receivers simultaneously, but if it emanates from any other position it arrives at different times, and if these time differences can be accurately determined and the velocity of propagation is known, the position of the source can be calculated (Fig. 19). This device, the introduction of which to marine service has been chiefly due to Professor Bragg, and which has been developed by Captain Boulding, has been of considerable service in the war for locating submarine explosions, apart from its well-known application for locating guns in land warfare; but it can obviously

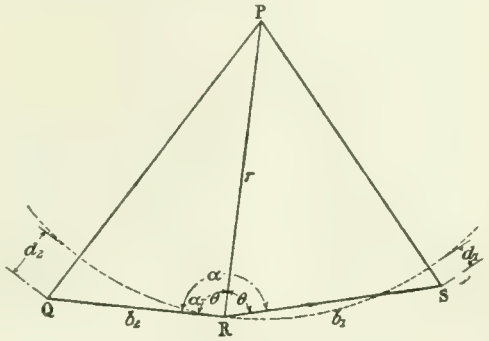


FIG. 19.—Three-station sound ranging.

be equally applicable for locating ships if they drop depth charges or employ other methods such as the Thornton spark for producing strong submarine impulses. It is of course necessary in this case for the ship to notify the sound-ranging station by wireless of its need for location, whereupon the station wirelesses back instructions to make the explosion and signals the location as soon as the result has been worked out.

Probably the most promising method of location would be by means of simultaneous wireless and sound impulses sent out at intervals from a fixed station. If the ship were provided with a wireless equipment and a hydrophone, either or both of them being directional, the direction of the source would be easily determinable, and its distance by the interval of time between the arrival of the two signals—nearly a mile for each second of interval. This may very likely prove to be far the most convenient and accurate method of location, and arrangements are being made for developing it.*

In the meantime great improvements have been effected in the ordinary three-receiver sound-ranging method with the object of simplifying the observation and determination of the source. Up to the present

* See paper on "Scientific Signalling and Safety at Sea," by Professor J. Joly, F.R.S., *Philosophical Magazine*, July 1918.

the times of arrival have been obtained by means of hydrophones connected to separate strings of an Einthoven galvanometer, which involves a photographic record which has to be developed and measured before the position can be calculated. Dr. A. B. Wood and Mr. Ford have greatly improved this process by what they call their phonic chronometer, which enables the times to be read directly on dials to an accuracy of 1/1,000th of a second. The principle is analogous to that of the author's roller stroboscope, in which a wheel with stroboscopic slits rolls on a cone which is kept revolving at a constant speed by a phonic wheel motor actuated from a standard tuning-fork.

In the phonic chronometer a vertical cylinder is maintained in rotation in the same manner, and three small pivoted discs are arranged to be pressed in contact with it by differentially-wound electromagnets when the current through one winding is broken. When the second circuit is also broken, the disc springs back from contact with the roller but immediately touches against a brake which stops it instantly. These discs are provided with pointers registering the times of contact to 1/1,000th of a second, and with light gearing extending the total time to 10 seconds or more, so that the three time intervals can be directly read off on the three dials. Apart from its value for sound-ranging, this chronometer should have most valuable applications for gunnery and general testing, as it is remarkably compact and reliable in comparison with any high-speed chronometer hitherto devised.

Instead of ordinary microphones the hydrophones employed with this device have single-point contacts, which are broken by the arrival of the impulse, but which can be restored by the operator through the agency of a magnetizing coil. Extremely sensitive receivers of this type have been devised by Mr. Burnside, who employs a hollow silver-plated iron ball to make contact with a point on the diaphragm. This ball is arranged to have perfectly neutral buoyancy in a liquid inside the receiver case, so that it has no gravity control, and it is attracted into contact with the disc by a small coil.

By means of these devices the time intervals for sound ranging can be read from the phonic chronometer immediately the impulse is received, but the calculation of the position of the source is very troublesome. One way of avoiding this was devised by Captain A. Anderson, and consists of using glass or celluloid sheets with a series of circles drawn on them. If the positions of the receivers are marked on a plan and the observed time differences are converted into distances struck off as circles with compasses round two of the receivers, the source should be at the centre of a circle passing through one station and touching the other two circles, and by moving the glass plate over the plan the required circle can be found and its centre marked.

Another device, due to the author, is called a sound-ranging locator. Three or more receiving stations may be used and marked on the plan. At one of these points a long parallel bar is pivoted, and a number of thin steel bands are attached to the end of this bar, and to graduated rods running through swivelling slides fixed at each of the other stations. These strips can be adjusted by screws at the end of the bar (like the tuning arrangements of a stringed musical instrument) and clamped so that the distance from the clamp to the zero of each scale is exactly the same as the distance from the clamp to the point of the bar. A slide is provided on the bar with a vertical slit through which the strips all pass. When a record is obtained, the scales of the rods are set to the time differences obtained from the chronometer, and the bar is rotated and the slide pushed along the bar till all the strips are taut. When this is the case the edge of the slit from which the strips radiate is over the source of disturbance, and a pricker enables this point to be marked on the plan. In order to avoid errors due to stretching of the strips by tensions introduced by pushing up the slider, a simple tension indicator is provided in each strip, and the slider is pushed up until the strips are all at the standard tension at which they were adjusted.

An instrument on the same principle appears to have been devised by Mr. H. M. Dadourian in the United States under the name of the phonotelemeter, and was mentioned in the *Physical Review* for August 1919, but was unknown when this instrument was designed, and no details have been obtained as to its construction.

By aid of this chronometer and locator it will probably be possible to determine the position of a source within a minute after the arrival of the impulse. Corrections have to be applied for the temperature of the water, which considerably affects the velocity of propagation, but these can easily be made by curves correcting the time differences observed to a standard temperature before setting them on the scales of the locator.

Detection and Location of Obstacles.

If a ship can locate its position in any weather, and guide itself to a harbour or through a channel in a fog, the only remaining danger is from obstacles such as icebergs, wrecks and rocks. It appears probable that the echo methods of detection already described will eliminate this danger, and echoes have frequently been obtained from ships, rocks and ledges, piers, and other obstacles both by sonic and by high-frequency acoustic methods.

In 1917 Fessenden appears to have obtained echoes from ships, rocks and icebergs, using his oscillator described in a previous section, but this device is nearly non-directional owing to the relatively low frequency employed (about 1,000 $\sim$ per second). It is, however, very powerful, so that when no disturbing obstacles are present good ranges should be obtainable.

High-frequency acoustic methods have given very good echoes with sharp directional indication on ships and rocks, but it is not yet known how far they will be successful with icebergs. These latter present special difficulty, as the elastic properties of ice do not differ so greatly from those of water as to give a high percentage of reflection, but from calculations already made it appears probable that icebergs of any moderate size will be detected and located without great difficulty. Probably the most reliable arrangement will be a combination of an acoustic device such as the Fessenden oscillator or Wrightson syren with high-frequency searching equipment.

Another device which may be of considerable service in navigation is the obtaining of soundings by echo methods from the bottom. This has already been carried out very successfully by M. Marti, who has obtained soundings in depths of from 60 to 160 metres to an accuracy of about a metre, from ships moving at speeds up to 10 knots, by the use of small explosive charges fired alongside the vessel. By this means valuable information as to position may be obtained and the approach to shoals or shores detected. The lecturer has recently devised a scheme for giving direct and continuous indication of the depth of water under a ship by a pointer indicator on the bridge.

A great deal of work has been done on submarine and aerial signalling both secret and otherwise, with the object of permitting ships to communicate with one another and thus avoid collisions.

One of these devices which may be mentioned is the improved form of photophone invented by Dr. A. O. Rankine and described before the Physical Society, in which a mirror is fixed on the lever of a phonograph diaphragm which forms an image of a bright illuminated grid on another similar grid. The amount of light transmitted varies with the vibration of the diaphragm and is concentrated on a selenium cell at the distant station. Remarkably clear speech is obtained in this manner and the device is easily adaptable to ordinary ship searchlights.

If all the above devices prove as successful as they appear to promise, it seems probable that before long the last remaining dangers will be eliminated from navigation, and that passages will be made without danger or delay in all weathers.

IV. GENERAL SCIENTIFIC RESEARCH.

We now come to the last section, dealing with fundamental scientific research. The great importance of a thorough knowledge of submarine physics, and especially of the transmission of disturbances of every character through the sea, has already been insisted on. Although a considerable amount of knowledge was gained during the war in the course of experimenting with various detectional devices, it was naturally of an incomplete and disconnected character. Immediately after the Armistice, however, the lecturer urged the importance of attacking these problems, before concentrating again on the detectional methods and devices which depend upon them, and the work at Shandon has been directed largely with this object.

The chief fundamental questions to be settled are the laws of propagation of acoustic, electromagnetic, and optical waves in the sea. In addition it is most necessary to have methods of measuring the absolute values of the energy, etc., transmitted and received, and for investigating the properties of various transmitters and receivers.

Acoustic research.—Even during the war valuable information was obtained in this direction under the guidance of Professor W. H. Bragg. The method of submarine sound ranging developed by him enabled much more precise measurements of the velocity of propagation of sound in sea water to be made than had been done formerly, and this value may be taken as 15,120 metres per second at 16·7° C. from the measurements of Captain Boulding, as compared with about 14,500 metres per second for fresh water. The variation of velocity with temperature, which is probably somewhat high, has not yet been determined, but experiments are in progress at Shandon.

The phenomena of reflection are frequently most embarrassing as they give rise to interference effects. If a source of sound or other vibrational disturbance P (Fig. 20) is situated beneath the surface, the waves produced by it are reflected at the surface, so that at any point, Q, the effect is that which would be produced by two sources P and P′, the latter being the mirror image of the former. Owing, however, to the half wave-length retardation which takes place at reflection of a free surface, these two sources are in opposite phases, so that as the distances from them to any point at the surface of the water are equal, their effects will cancel and no sound should be heard. As a matter of fact a most powerful submarine explosion is very little heard on a ship half a mile away, and what is

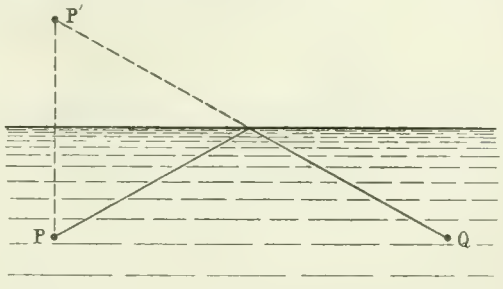


FIG. 20.—Acoustic interference.

heard may be caused by the deformation or breaking of the surface by the explosion, although this phenomenon may have another interpretation.* On the other hand if the point Q is in such a position that the two distances PQ and P′Q differ by half a wave-length, the disturbances should arrive in the same phase and reinforce one another. There are therefore a series of hyperboloidal shells surrounding the source in which the sound is a maximum or zero, and if the source is near the surface there will be a large "dark" space near the surface where the intensity is very low. Experimental evidence of these interference phenomena was obtained by Dr. A. B. Wood and Dr. F. B. Young at the Cullaloe Reservoir in 1917, and they require the most careful study because, since most listening has to be conducted within a few feet of the surface and a submarine may frequently be running only at periscope depth, they may very greatly increase the difficulty of hearing.

During the past year considerable development has been carried out on the metrical determination of sound intensities by Messrs. B. S. Smith and G. F. Partridge at Shandon. As a standard source of sound they use a transmitter excited by a high-alternating voltage derived from a valve oscillating set which produces sound waves of known amplitude. The received

* Professor Joly, however, claims that the sound from a submarine bell can easily be heard on a boat at a considerable distance.

intensity can be observed by a standard receiver connected to a three-valve resistance amplifier and a thermo-galvanometer. Potentiometer methods of measuring the amplification have been devised. Up to the present these methods have been employed chiefly for determining the characteristics of various forms of receivers and Fig. 21 shows the variation of the potential difference developed by a magnetophone for different frequencies, for a constant amplitude of the standard source. This curve strikingly shows the selective properties of the receiver owing to the natural frequency of its diaphragm, and illustrates

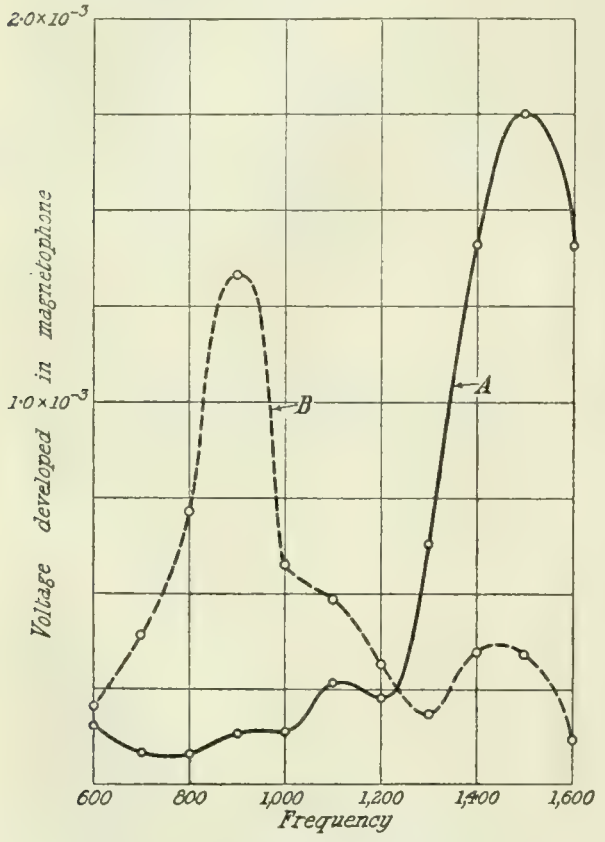


FIG. 21.—Calibration curves for air-drive magnetophone connected in line with a single 4,000-ohm ear-piece. Constant voltage of 800 volts at source, corresponding to a maximum amplitude of $2{\cdot}74 \times 10^{-5}$ cm.

Curve A.—Natural frequency of magnetophone reed; about 1,300 in air.
Curve B.—Natural frequency of magnetophone reed; about 600 in air.
Hydrophone at 2 cm. from source.

how such a receiver may modify or " colour " the nature of the sound received.

The lecturer has proposed to extend these methods for a complete investigation of the transmission and reflection of sound in the sea, but to employ the alternating-current potentiometer for the measurements, as this determines both the magnitude and phase of the disturbance. As this potentiometer will make measurements at a frequency of 1,000 ∿ per second to within 0·0001 volt, and within 0·1 or 0·2 degree of phase, it is particularly suitable for the purpose. At this frequency 1 degree of phase displacement corresponds to a time difference of 1/360,000th of a second, so that 0·2 degree corresponds to about one two-millionth of a second and the time required for an acoustic wave to travel only one foot can be determined to about one part in 400 or closer. By using a standard transmitter of spherical form, and employing the potentiometer in conjunction with a receiver and resistance capacity amplifier, measurements can be accurately made over short distances, and can therefore be carried out for a preliminary investigation in a moderate-sized tank without serious trouble from bottom and side reflections, which can be practically eliminated if necessary by suitable acoustic lagging. In this way temperature changes can be conveniently studied. For longer range work the Gareloch is remarkably suitable on account of its sheltered position and fair width and depth, though to obtain service conditions deep open sea is essential.

Electromagnetic propagation.—The importance of this research, on account of the high absorption of sea water, has already been emphasized, and a good deal of preliminary investigation has already been done on it. On first joining the staff of Parkeston Quay in January 1918 the lecturer made approximate measurements to ascertain the effect of absorption on the E.M.F. induced in a search coil lying on the bottom, in the middle of a rectangular loop 300×200 yards wide, laid in the mouth of Harwich harbour in about 20 ft. of water. These measurements were made by means of a galvanometer and rotating commutator on board a moored ship from which alternating current was supplied to the loop, and showed that at frequencies from 10 to 20 ∿ per second the loss of E.M.F. by absorption was only 10 to 20 per cent. The position of the loop was located by a search coil and telephone with amplifier similar to the arrangement afterwards employed for the aural leader gear. These tests were sufficient for the immediate purpose, but as soon as the leader gear experiments were commenced in the middle of the year, certain phenomena connected with it led to further investigation of the magnetic field surrounding the cable at sonic frequencies, with the result of discovering that this field was nearly horizontal at moderate distances from the cable, instead of nearly vertical as would be anticipated from the ordinary theory. When the visual leader gear was proposed, it was anticipated from the small amount of absorption found at sub-sonic frequencies that the distortion would also be small, but experiments soon showed that this was not the case, and a series of field disturbance tests were made by means of the inclined coils on H.M.S. " Auricula " at various frequencies from 10 to 50 ∿ per second showing large distortion which increased as the frequency was raised (see Fig. 17). In this connection it should be noted that the direction of the lines of force indicated on the diagram is only approximate near the points where the field is horizontal, as by connecting the coils in series it was possible to estimate the relative phases of the electromotive forces in the two coils, from which it appeared that the field was of an elliptically rotating character in this region. It must not be forgotten that these experiments were conducted on an iron ship, but the coils were so large and high that it is not probable that very serious

distortion was caused by the hull. A mathematical investigation indicated that the effect was most probably due to the "skin effect" in the water, which caused the return current from the end of the cable through the sea to crowd in upon and over the cable, and also to refraction of the electromagnetic waves on escaping from the sea into the air.

Preparations are now nearly completed at Shandon for a rigorous experimental investigation of this phenomenon, as it does not appear that it can be completely solved mathematically. For this purpose a wooden barge is being equipped with a tall wooden mast, to the upper and lower ends of which a pair of horizontal and vertical search coils are fixed for determining the two components of the magnetic field (Fig. 22). The mast can be raised and lowered by a cord and winch so that the two upper coils can be fixed at any desired height above the surface, and the two lower ones at any depth beneath it. In addition a long horizontal spar with electrodes at its ends is attached to the bottom of the mast, and leads brought along it which as well as the connections from the four search coils are brought into a multicore cable running to an observing hut on Shandon pier. This pier contains an alternating-current potentiometer which will measure the amplitude and phase of the E.M.F. induced in the search coils and of the potential difference between the electrodes which is proportional to the current density in the sea.

The cable is laid for a distance of about 2 miles along the loch as straight as possible and about 300 yards from the observation hut. At a point directly opposite the pier a junction box is inserted containing a 0·01-ohm resistance, the potential terminals of which are connected through a two-core cable to the potentiometer. This enables the magnitude and phase of the current to be determined in the portion of the cable where the measurements are being made, and eliminates the effect of attenuation, which may be of importance at the higher frequencies of 1,000–2,000 ∼ per second up to which it is proposed to carry the observations.

It is of course necessary to be able to keep the barge in a definite position relatively to the cable when observations are being made, and for this purpose a

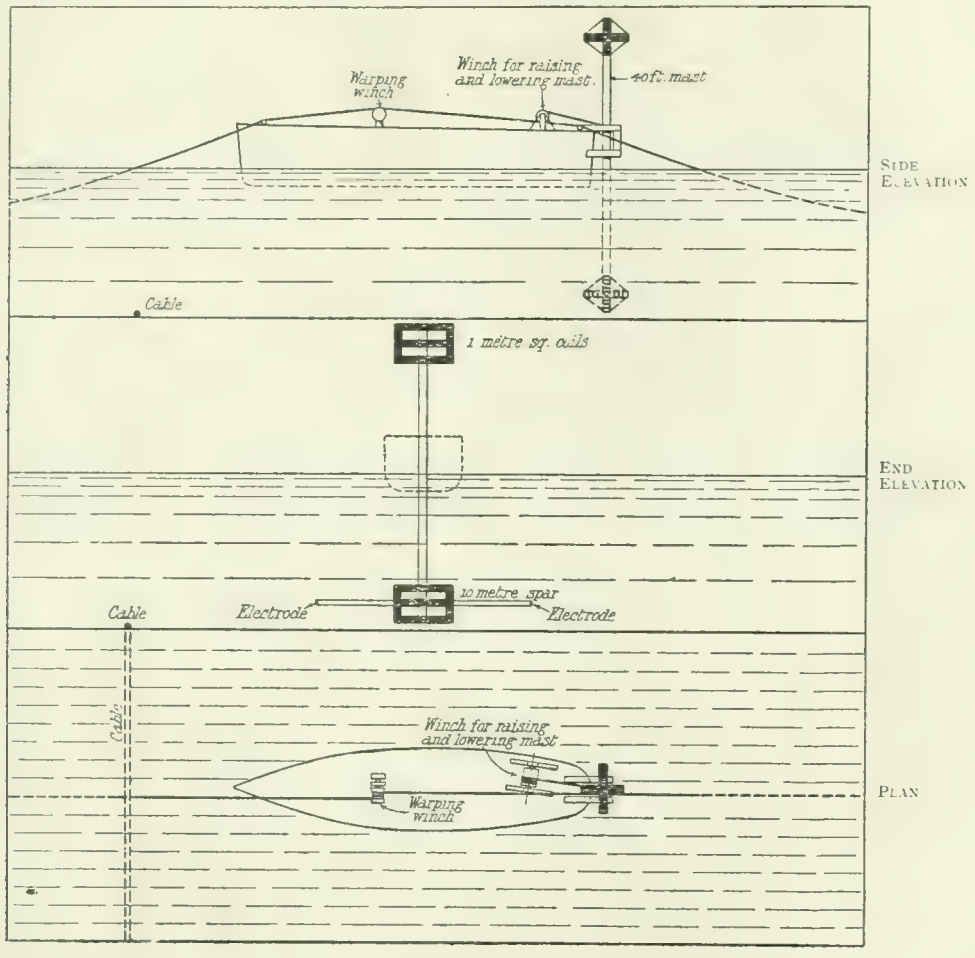


FIG. 22.—Arrangements for field and current distribution tests round submarine cable.

700-yard rope is run from the pier to a mooring in the Gareloch, and this rope passes over a winch drum on the barge, so that it can be warped along the rope into any position as in canal haulage. In calm weather it is hoped that this device will be effective. Ranges will be taken by a 9-ft. Barr and Stroud range finder installed in the observation hut.

In connection with these tests a second series of observations will be made on the electromagnetic field produced by circular and square coils when submerged. This is not only of great theoretical interest, but has an important bearing on the question of electromagnetic detection.

Appendix 3 gives an outline of the mathematical treatment of the subject, and a table of absorptions of plane electromagnetic waves of various frequencies is attached. For the purpose of this calculation a reliable determination of the specific resistance of sea water was required, and a Kelvin double-bridge arrangement was devised for the purpose. The measurements were carried out by Mr. H. Rivers Moore and gave a specific resistance of 27 ohms per cm. cube for water from Harwich Harbour mouth, and of 24 ohms per cm. cube for open sea water off Weymouth, with a temperature coefficient of — 3 per cent per degree Centigrade in each case. These values were found to be independent of current frequency and dimensions over wide limits. The table of attenuations has therefore been circulated for a specific resistance of 25 ohms per cm. cube.

Another point of great interest is the existence of electrical currents in the sea due to tidal and wave motion in the earth's magnetic field, which were predicted by Faraday and have been experimented with by Dr. F. B. Young. These require investigation, as their behaviour is complicated by the nature of the channel or sea bed. It is possible that their elucidation may have important consequences in relation to submarine telegraphy.

Optical transmission.—Little work other than of an immediately practical and empirical character appears to have been done in this direction. It seems desirable, however, to have definite data concerning the optical absorption of sea water for various wave-lengths, and photometric arrangements are being made to determine it. There are of course numerous other problems of a detailed character which have been dealt with, or which require solution, but these are of comparatively little general interest.

Testing and training of observers.—Apart from the improvement of detectional devices, there is the observational element to be dealt with, particularly in the case of acoustic detection and direction finding in which great differences are found between the discriminating and binauralling facilities of different individuals. A large amount of work has been done in the training of listening officers at the Hydrophone Station at Portland, but investigations are being made with the object of obtaining metrical data as to the acoustic and visual facilities of observers, particularly as regards colour vision.

Conclusion.

Although this account is somewhat long, it has not touched on the vast amount of work which has been done at the developmental Naval Stations at Portsmouth and elsewhere. Great advances in radio-telegraphy and telephony and in the design of thermionic valves and amplifiers have been made at the Signal School, and equally important developments in mining and torpedo construction and investigation have been made by the Mining School and Torpedo Stations, all under the "Vernon." Of great importance in another direction is the work carried out at the Admiralty Physical Laboratory at Wormwood Scrubbs under Professor J. C. McLennan, late Scientific Adviser to the Admiralty, which has resulted in the production of large quantities of helium gas for airships at a moderate cost. This may have a very important effect on the construction of glow lamps and thermionic valves.

Mention must also be made of the important work carried out by the Admiralty Compass Department at Slough, particularly in the development of the gyro compass which is of such great importance for submarine and general navigation, and as regards special compasses for aircraft.

As regards the future, as soon as the above-mentioned fundamental researches on transmission for which the Gareloch is specially suitable are completed, which will take about a year, the Shandon Experimental Station will be transferred to a new Admiralty Physical Laboratory to be built close to the National Physical Laboratory at Teddington, the sea experiments being conducted at Portsmouth or elsewhere. The general direction of scientific research at the Admiralty is now in the hands of the new Director of Scientific Research, Mr. F. E. Smith, F.R.S., who is co-ordinating the pure scientific research and experimental work with the developmental work of the existing Naval Stations. It is hoped in this way to obtain the maximum of efficiency and co-operation without undue overlapping.

Although the need for economy in all directions in Government expenditure is imperative, it appears probable that immense gain as regards navigation will result from the work already done and in progress; while the need for really reliable devices for submarine detection and destruction will be admitted by all. In view of the great difficulties associated with these problems, the results already achieved are remarkable and form a tribute to the initiative and resourcefulness of British scientific workers. The most obscure and apparently academic scientific phenomena have been pressed in to the service, and have been productive of valuable practical results, which will have their bearing on many branches of industry.

It only remains to add that the work has been continued since the end of the war without any abatement of enthusiasm or energy, although with greatly reduced numbers; and that those who have been fortunate enough to be associated with its fascinating problems are keenly desirous of applying them to the best service of the nation in peace as well as war.

APPENDIX 1.

Theory of Acoustic Transmission.

Let P and v (Fig. 23) be the pressure and velocity of the medium at any point at a distance x from the receiving end, Δ the density of the medium and E its elasticity.*

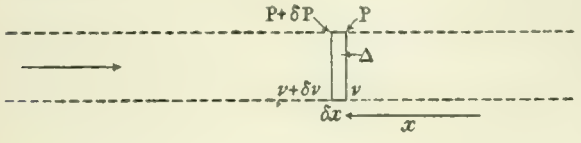


Fig. 23.

Then assuming a unit area of a plane wave-front and a lamina of thickness δx, the mass of the medium in the lamina is $\Delta \delta x$, which is accelerated by the difference of pressure δ P and

$$\delta P = \Delta \delta x \frac{\partial v}{\partial t}, \quad \text{or} \quad \frac{\partial P}{\partial x} = \Delta \frac{\partial v}{\partial t} \quad . \quad . \quad (1)$$

On the other hand the lamina is compressed by the increase of pressure and $\frac{d\delta x}{\delta x} = \frac{1}{E} \partial P$, but $\frac{\partial}{\partial t} \delta x = \delta v$,

hence
$$\frac{\partial v}{\partial x} = \frac{1}{E} \cdot \frac{\partial P}{\partial t} \quad . \quad . \quad . \quad . \quad . \quad (2)$$

These equations may be compared with the electrical case for cable transmission

$$\frac{\partial V}{\partial x} = R i - L \frac{\partial i}{\partial t} \quad . \quad . \quad . \quad . \quad . \quad (3)$$

and
$$\frac{\partial i}{\partial x} = G V - K \frac{\partial V}{\partial t} \quad . \quad . \quad . \quad (4)$$

which are evidently identical if V is substituted for P, i for v, L for Δ, and K for 1/E, R and G both being zero.

It will thus be seen that the two transmissions are physically similar, except that in the acoustic case the elasticity is due to the compressibility of the medium and the displacement is therefore longitudinal, while in the electrical case it is due to the lateral displacement in the dielectric. It is generally assumed in the acoustic case that there is nothing corresponding to resistance or leakance, and hence no attenuation, but this is of course not strictly true. In the passage of sound along tubes there is a frictional resistance to the motion corresponding to electrical resistance, while any energy lost in compression and rarefaction due to mechanical hysteresis is comparable with leakance. In this case we may write the acoustic equations as follows :—

$$\frac{\partial P}{\partial x} = f v + \Delta \frac{\partial v}{\partial t} \quad . \quad . \quad . \quad . \quad . \quad (5)$$

and
$$\frac{\partial v}{\partial x} = g P + \frac{1}{E} \cdot \frac{\partial P}{\partial t} \quad . \quad . \quad . \quad . \quad . \quad (6)$$

which are similar to the electrical cable equations (3) and (4) and which can be treated in a similar manner.

* The adiabatic elasticity which is γ times the isothermal elasticity must be taken in the case of acoustic propagation, as the variations of pressure and volume are so rapid.

In this case taking the simple relations (1) and (2) we have :—

$$\frac{\partial^2 P}{\partial x^2} = \frac{\Delta}{E} \cdot \frac{\partial^2 P}{\partial t^2} \quad \text{and} \quad \frac{\partial^2 v}{\partial x^2} = \frac{\Delta}{E} \cdot \frac{\partial^2 v}{\partial t^2}$$

both of which are of the same form.

The simplest case of a progressive sinusoidal wave is $P = P_{max.} \sin \frac{2\pi}{\lambda} (V t + x)$, where V is the velocity of transmission and λ the wave-length, in which case

$$\frac{\partial^2 P}{\partial x^2} = \frac{4\pi^2}{\lambda^2} P \quad \text{and} \quad \frac{\partial^2 P}{\partial t^2} = \frac{4\pi^2 V^2}{\lambda^2} P$$

so that $\frac{\partial^2 P}{\partial x^2} = \frac{1}{V^2} \times \frac{\partial^2 P}{\partial t^2}$, which satisfies the above relations if $V = \sqrt{(E/\Delta)}$, the well-known expression for the velocity of propagation.

Since $2\pi V/\lambda = 2\pi f = \omega$, where f is the frequency of oscillation, we may write

$$\begin{aligned} P &= P_{max.} \sin (\omega t + 2\pi x/\lambda) \\ &= P_{max.} [\sin \omega t \cos (2\pi x/\lambda) + \cos \omega t \sin (2\pi x/\lambda)] \end{aligned}$$

In vector notation $\cos \omega t = j \sin \omega t$, where $j = \sqrt{-1}$, so that

$$\begin{aligned} P_x &= P_{max.} \sin \omega t [\cos (2\pi x/\lambda) + j \sin (2\pi x/\lambda)] \\ &= P_{max.} \sin \omega t \, e^{j 2\pi x/\lambda} \end{aligned}$$

and if we denote $P_{max.} \sin \omega t$ by P, and $2\pi/\lambda$ by α, $P_x = P e^{j\alpha x}$, and since $\frac{\partial v}{\partial t} = j\omega v = \frac{1}{\Delta} \times \frac{\partial P}{\partial x}$ by (1),

$j \omega v_x = \frac{j \alpha P}{\Delta} e^{j\alpha x}$, and

$$v_x = \frac{\alpha}{\omega \Delta} P e^{j\alpha x} = \frac{2\pi}{\omega \lambda \Delta} P e^{j\alpha x} = \frac{P}{\sqrt{(E\Delta)}} e^{j\alpha x} = \frac{P}{\mu} e^{j\alpha x}$$

where $\mu = \sqrt{(E\Delta)}$, which is called the "acoustic resistance" of the medium by Brillé.* It corresponds in the electrical case to $\sqrt{(L/K)} = Z_0$ the "characteristic impedance" of the circuit. The phase of the pressure and velocity of displacement of the medium are therefore in unison at each point of the path, so that the displacement itself leads by $\frac{1}{2}\pi$, or is in quadrature with the pressure.

The energy in each complete wave

$$e = \int_0^\lambda P \, dx = \int_0^\tau P \frac{\partial x}{\partial t} dt = \int_0^\tau P v \, dt \text{ or } e = \tfrac{1}{2} P_{max.} v_{max.} \tau$$

so that the power transmitted from a continuously vibrating source $= \frac{1}{2} P_{max.} v_{max.} = \bar{P} \bar{v}$, where $\bar{P}$ and $\bar{v}$ are the R.M.S. values of P and v. This corresponds to the relation : power $= \bar{V} \bar{i}$ in an alternating-current circuit when V and i are in phase. It should be observed, however, that this assumes that there is no reflection at the receiving end, or that the energy is completely absorbed, which is equivalent in the similar electrical case to assuming a non-inductive receiver of resistance equal to Z_0 or μ, so that a given potential difference produces a current of the same value as that in the wave. In this case the efficiency of transmission is unity, so that in the acoustic case there will be no reflection on passing into a new medium if the value of $\mu = \sqrt{(E\Delta)}$ is the same in both media, and the efficiency of transmission

* *Le Genie Civil.*

will be perfect. This result is of the greatest importance as regards the construction of listening devices for highest efficiency.

In general $\mu = \sqrt{(E\,\Delta)}$ will not be the same in the two media, so that there will be a reflection at the interface. We may therefore write for the conditions on the two sides of the interface

$$P_{1x} = P_1 e^{j\omega t - \mu_1 x} + P_1' e^{-j\omega t + \mu_1 x}, \quad \text{and} \quad P_{2x} = P_2 e^{-j\omega t - \mu_2 x}$$

x being reckoned in each case away from the surface.

When x is zero $P_{1x} = P_1 + P_1'$, and $P_{2x} = P_2$, and it is evident that these two pressures must be equal as the pressure must be continuous.

Hence $P_1 + P_1' = P_2$ or $\mu_1 (v_1 + v_1') = \mu_2 v_2$, so that $v_1 + v_1' = (\mu_2/\mu_1)\, v_2 = r\, v_2$, where r is the ratio of the acoustic resistances of the two media.

It is also evident that there is no discontinuity of velocity, so that $v_1 - v_1' = v_2$.

Combining these two relations we have

$$v_2 = \frac{2}{r+1} v_1, \quad \text{and} \quad v_1' = \frac{r-1}{r+1} v_1$$

$$P_2 = \frac{2r}{r+1} P_1, \quad \text{and} \quad P_1' = \frac{r-1}{r+1} P_1$$

From which

Energy in transmitted wave

$$= \frac{4r}{(r+1)^2} \times \text{energy in original wave}$$

Energy in reflected wave

$$= \left(\frac{r-1}{r+1}\right)^2 \times \text{energy in original wave}$$

Hence the efficiency of transmission $= \frac{4r}{(r+1)^2}$ and of reflection $= \left(\frac{r-1}{r+1}\right)^2$.*

* It should be observed that the magnitude of all these expressions is unchanged if we write $1/r$ for r, which implies that the intensities of the transmitted and reflected waves, and the efficiency of transmission is the same if the direction of propagation is reversed. The phase of the reflected wave is, however, reversed as shown below.

As regards phase, it is evident that there is no change of phase either of pressure or velocity in the transmitted wave. For the reflected wave, however, the phase relations depend upon whether r is greater or less than unity, i.e. upon whether the second medium is more or less resistant than the first. If the second medium is more resistant $r > 1$, so that P_1' is positive, and is in phase with the pressure P_1 in the incident wave. In this case also v_1' is positive, but it has been taken with reference to the new direction of propagation away from the interface, and must therefore be regarded as in opposite phase to v_1. When r is less than unity these relations are reversed, so that we have :—

$r > 1$. Reflected pressure in phase, reflected velocity reversed or displaced by π.

$r < 1$. Reflected pressure reversed in phase or displaced by π, reflected velocity in phase.

$r = 1$. No reflected pressure or velocity, the whole of the energy being transmitted.

When r is very large, as in passing from air to steel or other highly resistant media, $P_1' = \frac{r-1}{r+1} P = P$ nearly, or the total pressure $P_1 + P_1' = 2P_1$ and the resultant velocity $v_1 - v_1'$ is zero. The efficiency of transmission $\frac{4r}{(r+1)^2}$ is then very low, and of reflection $\frac{(r-1)^2}{r+1}$ or nearly unity.

When r is very small, as in passing from steel or water to air, $P_1' = -P$, or the resultant pressure at the surface is nil, and $v_1' = -v_1$, so that the total velocity of the particles is $2v_1$. In this case also the efficiency of transmission is then very low, and of reflection nearly unity.

Brillé (loc. cit.) gives the following table of constants for various media :

TABLE 1.

Transmission of Vibratory Waves from One Medium to Another.

Nature of the Media	Value of E (kg. per sq. mm.)	Value of Δ (C.G.S.)	Value of $\sqrt{\left(\frac{E}{\Delta}\right)}$ (metres per sec.)	Values of $\mu = \sqrt{(E\,\Delta)}$ in units C.G.S.
Steel	2×10^4	7·8	5,100	395×10^4
Cast iron	$0{\cdot}95 \times 10^4$	7	3,680	258×10^4
Brass	$0{\cdot}65 \times 10^4$	8·4	2,780	234×10^4
Bronze	$0{\cdot}32 \times 10^4$	8·8	1,910	168×10^4
Lead	$0{\cdot}06 \times 10^4$	11·4	725	$82{\cdot}5 \times 10^4$
Wood (Teak)	$0{\cdot}10 \times 10^4$	0·86	4,300	37×10^4
Wood (Fir)	$0{\cdot}09 \times 10^4$	0·45	4,470	20×10^4
Wood (Beech)	$0{\cdot}06 \times 10^4$	0·8	2,740	22×10^4
Water	2×10^2	1	1,410	14×10^4
Rubber	Below 1 (variable according to the nature of the rubber)	1 approximately	Below 100	Below 1
Air	$1{\cdot}40 \times 10^{-2}$	0·0013	328	$0{\cdot}004 \times 10^4$

It will be seen from this how low the efficiency of transmission is in the case of water to air or to the steel side of a ship.

For water $\mu = 14 \times 10^4$, and for air $0{\cdot}004 \times 10^4$, so that $r = 0{\cdot}000286$ and the efficiency of transmission $\eta = \frac{4r}{(r+1)^2} = 0{\cdot}00114$, or $0{\cdot}114$ per cent approximately.

For steel $\mu = 395 \times 10^4$, so that for water to steel $r = 28$ approximately and the efficiency of transmission $\eta = \frac{4 \times 28}{29^2} = 0{\cdot}133$ or about 13 per cent, while for steel to air $r = \frac{0{\cdot}004}{395} = 0{\cdot}00001$ and $\eta = 0{\cdot}00004$ or $0{\cdot}004$ per cent.

For water to steel to air, as in a ship,

$$\eta = 0{\cdot}132 \times 0{\cdot}00004 = 4{\cdot}3 \times 10^{-6}$$

only, while for water to steel to water it is $0{\cdot}132 \times 0{\cdot}132 = 0{\cdot}017$ or $1{\cdot}7$ per cent, say 2 per cent allowing for multiple reflections in the steel. This is much higher than for water to steel to air, so that it has been found highly advantageous to enclose inboard hydrophones in water-filled tanks, the water being in contact with the steel hull. This device has long been in use by the Submarine Signal Company.

These figures exhibit the extraordinary small amount of acoustic energy which is communicated to the air even vertically above a sounding body in the water, and the even smaller amount which penetrates into the interior of an iron ship if the plates are thick. This forms one of the greatest obstacles to submarine listening, although fortunately the efficiency is not as low as these figures indicate, as the ship's plates are sufficiently thin to act to some extent as diaphragms.

It is evident that one of the most important problems in connection with submarine listening is to find materials of sufficient strength in which the acoustic resistance $\mu = \sqrt{(E\,\Delta)}$ is nearly the same as for water. From the above table it is seen that the only material which even approximates to this requirement is wood, in which μ varies from 22 to 37×10^4 as compared with 14×10^4 for water, but there is evidently room for further research on this point.

APPENDIX 2.

Theory of Three Station Sound Ranging.

Let P (see Fig. 19) be the point of disturbance; Q, R, and S, the three shock receivers; b_1 and b_2 the two "bases" R S and R Q; and d_1 and d_2 the two distances corresponding to the time differences observed.

Then $r^2 + 2\,r\,d_1 + d_1^2 = r^2 + b_1^2 \quad 2\,r\,b_1 \cos\theta$

and $r^2 + 2\,r\,d_2 + d_2^2 = r^2 + b_2^2 - 2\,r\,b_2 \cos(\alpha - \theta)$

from which $2\,r\left\{b_1 \cos\theta + d_1\right\} = b_1^2 - d_1^2$

and $2\,r\left\{b_2 \cos(\alpha - \theta) + d_2\right\} = b_2^2 - d_2^2$

hence $$\frac{b_2 \cos(\alpha - \theta) + d_2}{b_1 \cos\theta + d_1} = \frac{b_2^2 - d_2^2}{b_1^2 - d_1^2}$$

from which

$$\left\{(b_1^2 - d_1^2)\,b_2 \cos\alpha - (b_2^2 - d_2^2)\,b_1\right\}\cos\theta + (b_1^2 - d_1^2)\,b_2 \sin\alpha \sin\theta + (b_1^2 - d_1^2)\,d_2 - (b_2^2 - d_2^2)\,d_1 = 0$$

This expression does not lend itself to obtaining a simple general formula for θ, but is of the form $A \cos\theta + B \sin\theta + C = 0$, where A, B, and C can be numerically calculated from the record of any given explosion.

Then

$$\cos\theta = \left\{-A\,C + \sqrt{[A^2C^2 + (A^2 + B^2)(B^2 - C^2)]}\right\}(A^2 + B^2)$$

and $$r = \frac{b_1^2 - d_1^2}{2\,(b_1 \cos\theta - d_1)}$$

enabling the range and direction of the source to be calculated. If the three stations Q, R, and S are in the same straight line,

$$\alpha = \pi,\ \sin\alpha = 0,\ \cos\alpha = -1,$$

and $$\cos\theta = \frac{(b_1^2 - d_1^2)\,d_2 - (b_2^2 - d_2^2)\,d_1}{(b_1^2 - d_1^2)\,b_2 - (b_2^2 - d_2^2)\,b_1}$$

and $$r = \frac{\frac{1}{2}(b_1^2 - d_2^2)\,b_2 - (b_2^2 - d_2^2)\,b_1}{b_1\,d_2 - b_2\,d_1}$$

APPENDIX 3.

Propagation of Electromagnetic Wave in a Conducting Isotropic Medium.

Fundamental equations (expressing all units in C.G.S. electromagnetic measure).

(i) $$I = \dot{D} = \frac{1}{\rho}E - \frac{1}{9 \times 10^{20}} \cdot \frac{K}{4\pi}\dot{E},$$

(ii) $B = \mu H,$

(iii) $\operatorname{curl} E = \dot{B},$

(iv) $\operatorname{curl} H = 4\pi I = 4\pi \dot{D},$

where I = current, D = displacement, E = intensity of electric field, H and B = the magnetic force and induction respectively, K and μ the dielectric constant and permeability of the medium, and ρ its specific resistance.

Then from (iii) and (ii) $\operatorname{curl} E = -\dot{B} = -\mu\dot{H}$

$\therefore \operatorname{curl}\operatorname{curl} E$

$$= \nabla(\nabla E) - \nabla^2 E = \mu \frac{\partial}{\partial t}\operatorname{curl} H = -4\pi\mu\ddot{D} \text{ from (iv)}$$

but $\nabla E = 0$ by solenoidal condition

hence $$\nabla^2 E - \frac{4\pi\mu}{\rho}\dot{E} - \frac{K\mu}{9 \cdot 10^{20}}\ddot{E} = 0 \text{ from (i).}$$

In a similar manner we get

$$\nabla^2 H - \frac{4\pi\mu}{\rho}\dot{H} - \frac{K\mu}{9 \cdot 10^{20}}\ddot{H} = 0$$

Both these equations are of the form (taking the axis of x as the direction of propagation):

$$\frac{\partial^2 y}{\partial x^2} - \frac{4\pi\mu}{\rho} \cdot \frac{\partial y}{\partial t} - \frac{K\mu}{9\ 10^{20}} \cdot \frac{\partial^2 y}{\partial t^2} = 0$$

where y represents either E or H.

Assuming $y = E e^{-ax} \sin(\omega t - b x)$, where $\omega = 2\pi f$,

and f is the frequency. V = velocity of propagation $= \omega/b$, and λ the wave-length $= 2\pi/b$, we get

$$a^2 - b^2 - \frac{K\mu\omega^2}{9 \times 10^{20}} = 0 \quad \text{and} \quad a\,b - \frac{2\pi\mu\omega}{\rho} = 0$$

from which

$$a = \left[\frac{1}{2}\left(\frac{K\mu\omega^2}{18 \times 10^{20}}\right)^2 + \frac{4\pi^2\mu^2\omega^2}{\rho^2}\right]^{\frac{1}{2}} + \frac{K\mu\omega^2}{18 \times 10^{20}}\Bigg]^{\frac{1}{2}}$$

and

$$b = \frac{2\pi\mu\omega}{\rho\,a}$$

Case 1.—If ρ or ω is large, so that the second term under the radical is small compared with the first $a = \frac{6\pi \times 10^{10}}{\rho}\sqrt{\left(\frac{\mu}{K}\right)}$, which is independent of frequency, and $b = \frac{\sqrt{(K\mu)}}{3 \times 10^{10}}\omega$ approximately, so that for a medium of high resistivity the velocity of propagation $V = \frac{3 \times 10^{10}}{\sqrt{(K\mu)}}$, the attenuation constant

$$a = \frac{6\pi \times 10^{10}}{\rho}\sqrt{\left(\frac{\mu}{K}\right)}$$

and the wave-length $\lambda = \frac{3 \times 10^{10}}{f\sqrt{(K\mu)}}$. The velocity and wave-length are therefore independent of the resistivity, and the attenuation is proportional to the conductivity, being zero for a perfect insulator.

Case 2.—If ρ or ω is small so that the first term under the radical is the smaller

$$a = b = 2\pi\sqrt{\left(\frac{\mu f}{\rho}\right)},\ v = \sqrt{\left(\frac{\rho f}{\mu}\right)},\ \text{and}\ \lambda = \sqrt{\left(\frac{\rho}{\mu}\right)}$$

and in the distance of one wave-length either H or E is reduced to $e^{-2\pi} = 0{\cdot}001865$ of its initial value.

In order that the simple expression $a = 2\pi\sqrt{\left(\frac{\mu f}{\rho}\right)}$ should be within 1 per cent of the value of the complete expression for a above, $\frac{K\mu\omega^2}{18 \times 10^{20}}$ should not be greater than 1/50th of $2\pi\mu\omega/\rho$ from which taking K as 80,* μ as unity and $\rho = 25 \times 10^9$, the frequency $f = 18 \times 10^6$ periods per second.

For all frequencies up to this value, therefore, which covers all practical frequencies, the attenuation may be taken as $2\pi\sqrt{\left(\frac{\mu f}{\rho}\right)}$ without sensible error, for sea water or other media in which ρ does not exceed the above value.

The attached approximate table of velocities, wave-lengths, and attenuations has been calculated for the value of ρ of 25 ω per cm. cube.

* The value of K is difficult to determine for such a conducting medium as sea water, and very different results have been given, but the above is the highest value which we have seen.

PROPAGATION OF ELECTROMAGNETIC WAVES IN SEA WATER.

Table of Velocities, Wave-lengths, and Attenuations for Various Frequencies.

Calculated for Specific Resistance $\rho = 25$ ω per cm. cube.

Frequency per sec.	Velocity km. per sec. $= 1{\cdot}580\sqrt{f}$	Wave-length, metres $= 1{,}580 \div \sqrt{f}$	Attenuation constant $a = 3{\cdot}97 \times 10^{-5}\sqrt{f}$	Intensity transmitted*	
				100 metres $e^{-0{\cdot}397\sqrt{f}}$	1 km. $e^{-3{\cdot}97\sqrt{f}}$
0	0	∞	0	1	1
5	3·533	706·6	0·0000888	0·4115	$1{\cdot}392 \times 10^{-4}$
10	4·996	499·6	0·0001258	0·2842	$3{\cdot}437 \times 10^{-6}$
15	6·119	407·9	0·0001538	0·2149	$2{\cdot}091 \times 10^{-7}$
20	7·066	353·3	0·0001775	0·1695	$1{\cdot}959 \times 10^{-8}$
30	8·654	288·5	0·0002174	0·1137	$3{\cdot}62 \times 10^{-10}$
40	9·993	249·8	0·0002511	0·0813	$1{\cdot}244 \times 10^{-11}$
50	11·17	223·4	0·0002807	0·0604	$6{\cdot}463 \times 10^{-13}$
100	15·8	158·0	0·000397	0·01857	$5{\cdot}728 \times 10^{-18}$
200	22·35	111·7	0·0005614	$3{\cdot}653 \times 10^{-3}$	$4{\cdot}232 \times 10^{-25}$
300	27·37	91·23	0·0006876	$1{\cdot}032 \times 10^{-3}$	$1{\cdot}374 \times 10^{-30}$
500	35·33	70·66	0·0008877	$1{\cdot}392 \times 10^{-4}$	$2{\cdot}733 \times 10^{-39}$
700	41·8	59·71	0·0010503	$2{\cdot}745 \times 10^{-5}$	$2{\cdot}432 \times 10^{-46}$
1,000	49·96	49·96	0·001258	$3{\cdot}437 \times 10^{-6}$	$2{\cdot}3 \times 10^{-55}$
1,200	54·73	45·61	0·001375	$1{\cdot}066 \times 10^{-6}$	$1{\cdot}901 \times 10^{-60}$
1,500	61·19	40·79	0·001538	$2{\cdot}091 \times 10^{-7}$	$1{\cdot}622 \times 10^{-67}$
2,000	70·66	35·33	0·001775	$1{\cdot}959 \times 10^{-8}$	$8{\cdot}325 \times 10^{-78}$
5,000	111·7	22·34	0·002807	$6{\cdot}463 \times 10^{-13}$	$1{\cdot}272 \times 10^{-122}$
10,000	158·0	15·8	0·00397	$5{\cdot}728 \times 10^{-18}$	$7{\cdot}58 \times 10^{-173}$
20,000	223·5	11·17	0·005614	$4{\cdot}232 \times 10^{-25}$	$1{\cdot}549 \times 10^{-244}$
50,000	353·3	7·066	0·008877	$2{\cdot}733 \times 10^{-39}$	$3{\cdot}02 \times 10^{-386}$
100,000	499·6	4·996	0·01258	$2{\cdot}3 \times 10^{-55}$	$4{\cdot}467 \times 10^{-547}$
200,000	706·6	3·533	0·01775	$8{\cdot}325 \times 10^{-78}$	$1{\cdot}318 \times 10^{-771}$
500,000	1,117·0	2·234	0·02807	$1{\cdot}272 \times 10^{-122}$	$1{\cdot}00 \times 10^{-1219}$
1,000,000	1,580·0	1·58	0·0397	$7{\cdot}58 \times 10^{-173}$	$6{\cdot}309 \times 10^{-1725}$

* Compared with the intensity when no absorption is present.

APPENDIX 4.

Transmission of Alternating Currents through Large Conductors.

If current is supplied to the sea through two electrode plates at a large distance apart, the supply leads being at a considerable distance, the currents in the sea pass from one electrode to the other like lines of magnetic force from one magnet pole to another, and if the supply is direct and the electrodes are very far apart, the current density will be sensibly uniform at all points near the line joining the electrodes and near the middle of their course. But if the supply is alternating the familiar "skin effect" will come into play, and the current will tend to diverge away from the axis so as to diminish the magnetic flux surrounding it. This phenomenon has been mathematically treated by Lord Kelvin, Professor A. Gray and Dr. Alexander Russell, for concentric cylindrical conductors. It cannot probably be solved for many other cases, but the results are of interest as showing the probable character of the current distribution.

Assuming, therefore, that the water is enclosed in a channel or pipe of circular section far away from the supply leads it can be shown that the current density Δ in the water is controlled by the equation

$$\frac{\partial^2 \Delta}{\partial r^2} + \frac{1}{r}\cdot\frac{\partial \Delta}{\partial r} = \frac{4\pi\mu}{\rho}\cdot\frac{\partial \Delta}{\partial t}$$

where r is the radius from the axis, μ the permeability of the conductor, and ρ its specific resistance. This is the well-known Fourier-Bessel form of equation, and if we write $\Im$ for the operator $r\frac{\partial}{\partial r}$ so that $\Im\,\Delta = r\frac{\partial \Delta}{\partial r}$, it becomes $\Im^2\,\Delta = \frac{4\pi\mu r^2}{\rho}\cdot\frac{\partial \Delta}{\partial t}$.

Then if we assume that Δ is a simple harmonic function of the time, and that its magnitude and phase are functions of r we may write $\Delta = f(r)\sin\{\omega t + \phi(r)\}$ or $= f(r)\sin\theta$ and

$$\Im^2\Delta = [\Im^2 f(r) - f(r)\{\Im\phi(r)\}^2]\sin\theta$$

$$-[f(r)\,\Im^2\phi(r) - 2\,\Im f(r)\,\Im\phi(r)]\cos\theta = \frac{4\pi\mu r^2\omega}{\rho} f(r)\cos\theta$$

which gives us the two relations

$$\Im^2 f(r) - f(r)\{\Im\phi(r)\}^2 = 0$$

and $$f(r)\left\{\Im^2\phi(r) - \frac{4\pi\mu\omega}{\rho}r^2\right\} + 2\,\Im f(r)\,\Im\phi(r) = 0$$

If we develop $f(r)$ and $\phi(r)$ in series of ascending powers of r or more conveniently of $r\sqrt{(4\pi\mu\omega/\rho)} = u$, we get by equating coefficients

$$\Delta_r = \Delta_0\{1 - 0{\cdot}1625\,u^4 - 1{\cdot}017\times 10^{-4}\,u^8 + 1{\cdot}594\times 10^{-6}\,u^{12} + 3{\cdot}66\times 10^{-8}\,u^{16} + \text{etc.}\}$$

and

$$\sin\{\omega t + 0{\cdot}25\,u^2 - 1{\cdot}737\times 10^{-3}\,u^6 + 3{\cdot}09\times 10^{-5}\,u^{10} - 7{\cdot}35\times 10^{-7}\,u^{14} + \text{etc.}\}$$

where Δ_r is the current density at any zone of radius r_x and Δ_0 is the density at the axis, a series which is fairly convergent for values of u up to 2, but not higher.

Figs. 24 and 25 show the variation of current density and phase as u increases from zero to 2, or r increases from zero to $\sqrt{[\rho/(\pi\mu\omega)]}$. The current density is about 24 per cent higher at this latter radius than

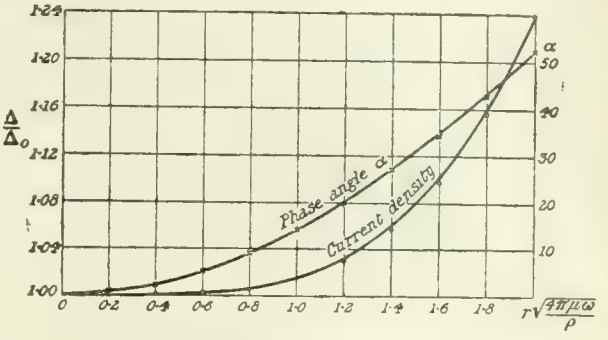


FIG. 24.—Skin effect in conductor: variation of current density and phase angle.

at the axis, and its phase is advanced by about 52°. These results can be fairly closely expressed by the empirical formula

$$\Delta = \Delta_0\cosh 0{\cdot}17\,\mu^2\sin\{\omega t + 0{\cdot}25 + 1{\cdot}875\}$$

from which the curves in Fig. 24 have been drawn, the points marked being obtained by the above series. The

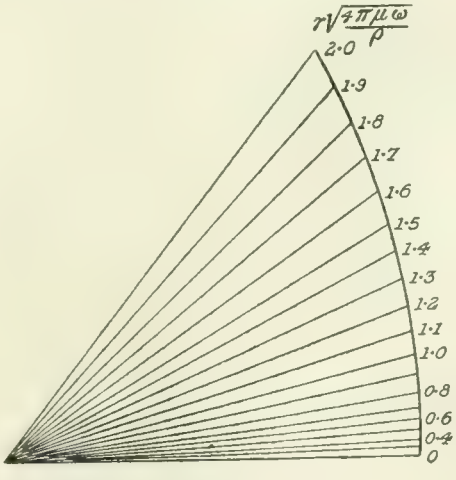


FIG. 25.—Vector diagram of current density.

agreement is sufficiently close to justify the extension of this formula to greater radii, although the calculations can be made more accurately by the ordinary tables of Bessel functions. There is little value, however, in extending the calculations to large radii, as the whole theory depends on the assumption that the equipotential surfaces are planes perpendicular to the axis, which is only true for moderate ranges when the current is supplied at small electrode plates, and also

on the assumption that the conductor is cylindrical and at the centre of a concentric return. The calculations show, however, that the "skin effect" is of serious importance in a large body like the sea, even at moderate frequencies.

Since ρ for sea water $= 25 \times 10^9$ C.G.S. units and $\mu = 1$, the radius at which the current density is increased by 24 per cent and its phase advanced by 52° is $r = \sqrt{\left(\frac{\rho}{\pi \mu \omega}\right)} = \frac{35{,}600}{\sqrt{f}}$ cm. or $\frac{356}{\sqrt{f}}$ metres, so that if the frequncy f is 10 ∿, $r = 112{\cdot}5$ metres, and at a good sonic frequency of 1,000 ∿, $r = 11{\cdot}25$ metres only. In this case the currents in the water tend to concentrate towards the surface of the water and the sides and bottom of the channel. They also tend in the practical case to concentrate towards the side of the channel on which the supply lead is, unless this is at a considerable distance compared with the width of the channel.

APPENDIX 5.

Current and Field Distribution in a Conducting Medium surrounding a Cable carrying an Alternating Current.

In the preceding section the distribution of current has been dealt with when it is introduced into the water by two electrode plates at a considerable distance apart. A far more important case, however, is that of a cable lying along the bottom with electrodes at its ends, so that the water may be taken as a return conductor surrounding the cable. In this case the "skin effect" is in the opposite sense, tending to cause the return currents to converge inwards towards the cable, so as to reduce the magnetic flux encircling it, and this is of importance as it has often been hastily assumed that the skin effect always tends to make the current concentrate towards the surface of the water.

Dealing first with the water as if it were a cylindrical conductor with the cable along its axis, we find that the same fundamental equation

$$\frac{\partial^2 \Delta}{\partial r^2} + \frac{1}{r} \cdot \frac{\partial \Delta}{\partial r} = \frac{4 \pi \mu}{\rho} \cdot \frac{\partial \Delta}{\partial t}$$

holds as for the inner conductor.

For a sinusoidal supply of frequency f, for which $\omega = 2 \pi f$, this becomes $\nabla^2 \Delta = j \frac{4 \pi \mu \omega}{\rho} r^2 \Delta$, and if we write K for $\sqrt{\left(\frac{4 \pi \mu \omega}{\rho}\right)}$ and u for the ratio r/r_c, where r is the depth of the zone considered, and r_c is the radius of the outer conductor, we find by the same process as before, if Δ_c is the current density at the circumference (assuming the inner conductor to be negligibly small),

$$\Delta_r = \Delta_c \left\{ 1 + \tfrac{1}{12} \mathrm{K}^4 u^4 + \tfrac{1}{15} \mathrm{K}^4 u^5 + \tfrac{23}{360} \mathrm{K}^4 u^6 + \tfrac{17}{240} \mathrm{K}^4 u^7 + \ldots \right\}$$
$$\sin \left\{ \omega t - \tfrac{1}{2} \mathrm{K}^2 u^3 + \tfrac{1}{8} \mathrm{K}^2 u^4 + \tfrac{1}{10} \mathrm{K}^2 u^5 + \ldots \right\}$$

This series is only reasonably convergent for all values of u, when K is not greater than unity, or r_c is not greater than $\sqrt{[\rho/(4 \pi \mu \omega)]}$. For K = 1 we have the following:—

u	0	0·1	0·2	0·3	0·4
Δ_r / Δ_c	1·000	1·000001	1·000159	1·000897	1·00318

0·5	0·6	0·7	0·8	0·9	1·0
1·00876	1·0179	1·0437	1·0854	1·156	1·278

Lead of phase ϕ: 0 0·296° 1·233° 2·902° 5·44° 8·96° 13·25° 19·93° 28·0° 38·4° 51·1°

so that the current density in the water close to the inner conductor is about 28 per cent higher than at the circumference of radius $\sqrt{[\rho/(4 \pi \mathrm{K} \mu \omega)]}$ (=56·5 metres at 10 ∿, or 5·65 metres at 1,000 ∿ in sea water), and its phase is advanced about 51°. We could make calculations for greater distances by employing Bessel functions, but it is of little use to do so, as we are not dealing in practice with a cable suspended in the centre of a cylindrical body of water, and the calculation has only been made with the object of showing that the current tends to converge inwards on the conductor and away from the surface and sides. As the total return current in the sea is equal and opposite to that in the cable, it tends to neutralize its magnetic effect at points above the surface; and at high frequencies, where the return current concentrates closely round the cable, the neutralization is almost complete, as in an ordinary concentric cable.

The fact that the current lags in phase as we proceed outwards from the cable, shows that we may consider the return current as moving outwards in the form of cylindrical waves, and it will be seen that the fundamental formula $\frac{\partial^2 \Delta}{\partial r^2} + \frac{1}{r} \cdot \frac{\partial \Delta}{\partial r} = \frac{4 \pi \mu}{\rho} \cdot \frac{\partial \Delta}{\partial t}$ reduces to $\frac{\partial^2 \Delta}{\partial r^2} = \frac{4 \pi \mu}{\rho} \cdot \frac{\partial \Delta}{\partial t}$ when r is very large, which is the same equation as that obtained for plane waves in Appendix 3, if the capacity term is neglected, as was shown to be permissible for sea water. Beyond a certain distance from the cable, therefore, the electromagnetic disturbance proceeds outwards in the form of waves with a velocity $v = \sqrt{(\rho f / \mu)}$.

Next considering the practical case of a cable laid along the sea bottom, we must take the earth or rock below the cable as being of low conductivity compared with the water, so that the bulk of the return current is confined to the latter. The mathematical solution of the distribution in this case would be an extremely complex matter, but from general considerations it will be seen that the current tends to concentrate towards the cable but above it.

We may perhaps form a rough mental picture of the field distribution in this case by regarding the return current as acting as if it were concentrated in a lamina above the cable, or more simply in two filaments one on each side above it. This gives a distribution not unlike that actually obtained in Fig. 17, but this applies to the field beneath the surface.

The matter is, however, further complicated by the fact that the electromagnetic waves proceeding outwards from the cable are refracted and reflected at its surface. It has been mentioned above that the velocity of propagation of electromagnetic waves in a conducting medium is $\sqrt{(\rho f/\mu)}$ compared with $3 \times 10^{10}/\sqrt{(K'\mu')}$ for air, so that the "refractive index," which is the ratio of the velocities, is $3 \times 10^{10} \div \sqrt{(\rho f)}$, since the permeabilities are the same and K'=1. For a frequency of 10 $\sim$ per second and $\rho = 25 \times 10^9$, this gives a refractive index of 6×10^4, so that almost complete internal reflection should be produced, were it not for the fact that the wave-length in the water at this frequency $\lambda = \sqrt{[\rho/(\mu f)]}$ is 500 metres, or about 14 times the depth in the experiments.

The whole problem therefore resolves itself into the distribution of current and magnetic field in and above a semi-opaque lamina of thickness which is in many cases small compared with the wave-length, and it seems necessary to investigate it experimentally.

DISCUSSION ON

"STANDARDIZATION RULES FOR ELECTRICAL MACHINERY" (BRITISH STANDARD SPECIFICATION No. 72).

BEFORE THE SOUTH MIDLAND CENTRE, AT BIRMINGHAM, 11 FEBRUARY, 1920.

Mr. A. R. Everest: Six years ago a discussion upon this subject took place before this Territorial Centre. Since that time much has happened. Following a long period of enforced inactivity due to war conditions, the International Electrotechnical Commission has now resumed its activities; this at the present time should have an added interest for members of the Institution, since our President, Mr. Roger T. Smith, attended the I.E.C. Meeting at Paris last May as Chairman of the British delegation, and also took a prominent part in the I.E.C. Plenary Meeting held in London last October. As a result of these resumed activities many of the essential points which were still unsettled in the I.E.C. Rules have now been settled, and the first volume is in the printer's hands. The general plan is that the I.E.C. Rules shall establish the essential principles as internationally agreed, the various countries participating then each preparing its own set of National Rules embodying the principles laid down by the Commission and a new edition of the British Standardization Rules (E.S.C.72) will be undertaken in the immediate future. The preoccupation due to war conditions, the cessation of export business and concentration of domestic business upon Government requirements, together perhaps with a certain want of appreciation of the new methods of rating, have all operated to delay the adoption of a new Standard Specification differing from the practice of the past. All of which goes to show that the present discussion is particularly opportune, and its conclusions should be of material assistance to the Committee dealing with the revision of British Standard Specification No. 72. It is, therefore, useful to consider the extent to which new light has recently been thrown upon the subject.

Overloads.—It is now well known that a machine when given the "British Standard continuous rating" is rated for the highest load which it can carry for an unlimited period without exceeding the limits of temperature-rise allowed by the Rules. There has been much misconception regarding the feasibility of allowing a machine so rated to take overloads in excess of its rating. The I.E.C. Rules are now so worded as to show clearly that the rating is a test rating for comparison purposes, and, as regards service conditions, the only limitation found in the Rules is that the machine shall not be subjected to any loads which cause it to acquire a temperature-rise higher than that allowed under the test condition. Clearly, a machine when starting cold could take a very considerable overload while still keeping within this limit. But undoubtedly there are dangers associated with very excessive overloads. Against these dangers there appears to be at present no safeguard in the British Rules, which impose no restriction on overload except in terms of temperature-rise. It appears desirable, therefore, that there should be an agreed limit upon the magnitude of the sustained overload to which a Standard machine may be subjected. As regards momentary overloads, the I.E.C. Rules now recognize (note to Clause 9) that when the overload peaks in service exceed the values agreed as suitable limits for a Standard machine, such service will demand a special machine with a special kind of rating. In the case of a Standard machine, therefore, it would appear desirable to establish recognized limits to the magnitude of both the sustained and momentary overloads. For this purpose it has been suggested that a sustained overload of 25 per cent for half an hour should be recognized for all motors not smaller than 5 h.p. This is, of course, subject to the rule that the standard temperature-rise must not be exceeded,

but it is considered that the need for such overload margin occurs chiefly when a cold motor is starting cold machinery.

Short-time ratings.—As regards short-time ratings little need be said, as the method of rating provided in the Rules corresponds to that which has been general practice for some time past.

Cooling conditions.—The " British Standard " rating (with its associated limit of temperature-rise is, by the Rules, suitable for use in connection with cooling air of temperature not exceeding 40° C. (104° F.) as a maximum. The need for additional ratings suitable for use under tropical conditions on the one hand, and under abnormally cool conditions on the other hand, have been discussed. It is proposed to establish a " Tropical Rating " with an appropriate higher limit to the maximum temperature of cooling air. Whether this shall be 50° C. (120° F.), or 55° C. (131° F.), or some other value is not yet decided. The first-mentioned limit would reduce the permissible temperature-rise under rated load by 10 degrees C., while the second value mentioned would involve a reduction of 15 degrees C. of the temperature-rise permissible at rated load, as compared with the temperature-rise allowed on machines intended for cooling air which does not exceed 40° C. Considered recommendations regarding the choice of 10 degrees C. or 15 degrees C. difference for this purpose would be of great assistance. As regards machines intended for cool countries, it is pointed out that those when used indoors are generally working under conditions not very different from those in temperate countries, and it is recommended that no special modifications shall be made for such cases. Those unusual cases in which a machine will certainly be required to operate always under abnormally low cooling conditions should be regarded as quite special, and designs made accordingly. The general rule for all such special designs would be, that when tested under rated load the temperature-rise should be such that when added to the temperature of the cooling conditions contemplated, the highest temperature obtained must not exceed the limits of total temperature indicated in the Rules.

Measurements of temperature-rise.—Another feature of considerable interest is the method recognized for measuring temperatures. The requirements of the earlier edition of the Rules, that temperature-rise measurements of field coils and similar windings should always be by resistance method, have been regarded as impracticable, particularly as regards small machines produced in large numbers. This objection has been met in later editions of the Rules by permitting these measurements to be made by thermometer alone, provided that readings so obtained are consistent with the limits assigned to the resistance method, as shown by complete tests taken on a few typical machines. There is a strong feeling among engineers that for turbo-alternators, and for other large and important machines, the temperature-rise should be determined from measurements made by embedded temperature detectors built into the machine at points so selected as to give indication of the internal temperature. The method is not unfamiliar—it has been employed in a number of special cases in this country, and has been used extensively abroad, both in America and on the Continent. The last (1917) edition of the British Standardization Rules No. 72 recognizes the advantage of these devices, but provided that until further information has been accumulated regarding the limits associated with their use, the acceptance of the machine should not be dependent upon the measurements made by this method. The commission has not as yet formulated definite Rules, but they have submitted for the consideration of the British and other National Committees a proposal on the following lines :—

> " That for the acceptance tests of large rotating machines the temperature should be measured by the embedded temperature detector method for parts where this method would be applicable."

It is not considered that the method would be applicable to any moving parts, but that it would be applied to windings in slots on the stationary part of a machine, the embedded temperature detectors being placed between coil and adjacent slot wall, and between coil and coil in the slot, in each case being outside the coil insulation. (The insertion of embedded temperature detectors within the insulation of the coil, adjacent to the copper, is not considered feasible for commerical tests on account of the risks involved, such measurements belonging essentially to research tests.) The proposal is that this method of temperature measurement should be employed for the stationary windings of machines meeting the foregoing conditions when such machines are wound for more than 5,000 volts, or are rated for an output exceeding 750 k.v.a., or if the stator cores exceed 20 inches axial length. The proposal contemplates that the method also may be applied to the windings of large transformers, provided this is specified in the contract. The recognition of this method of temperature measurement for the acceptance tests involves also the establishment of limits proper for the temperatures when so measured, and the British Committee is arranging to collect evidence with a view to forming conclusions upon this important point.

High-pressure tests.—There is little that is essentially new in connection with this subject. The injurious effects of long continued, severe high-pressure tests are becoming more and more recognized, and while the one-minute test still remains as the standard, suggestions have been made regarding the desirability of substituting one or more briefer tests of higher value, allowing time between such tests for the insulating material to return to its normal condition.

It is hoped that this brief review will suggest the principal points upon which discussion might be usefully centred with a view to bringing the new Standardization Rules into harmony with the ideas suggested by the best engineering experience. Finally, it may be noted that most of the points which may be regarded as still unsettled apply essentially to machines of large size and high voltage. As regards the smaller and more usual size machines, the explanatory notes of the I.E.C. Rules as now being issued will, no doubt, tend to remove any obscurity which has existed re-

garding the advantages to be gained by the adoption of a standard method of rating which shall be international.

Dr. M. Kahn : Mr. Everest's notes on the Rules for Electrical Machinery clear up a number of controversial points and foreshadow a revised edition, which contains several important improvements. It would be of considerable help if, together with the new Rules, a complete series of explanatory notes of the various regulations and recommendations were issued. The present Rules do not contain any standard tests, which are necessary to ascertain whether electrical machinery complies with the guarantees and specifications given in connection with it. This refers more particularly to efficiency and power factor, which can be determined in various ways. Standard margins which can be allowed in connection with these guarantees could also be embodied in the Rules on the lines of the recommendations of the B.E.A.M.A. The proposed extension of the Rules for temperature measurements on large generators by thermo-couples or resistance coils is a step in the right direction. In large modern turbo-alternators, where the eddy-current loss in the stator conductors is reduced by suitable means as described in Mr. Taylor's paper on "Eddy Currents in Stator Windings," the temperature gradient between conductors of a two-layer winding is small, and if a temperature detector is inserted between the top and bottom coil of such windings, it will indicate the temperature-rise of the conductors pretty closely although it is not in direct contact with the copper. Alternatively, such detectors may be placed between the coil and the wood or fibre wedge closing the top of the slot. As the heat conductivity of the wedge is low the temperature gradient between the copper and the outside of the insulating tube is not appreciable at this point. If the neutral of the alternator is earthed a few detectors can be inserted inside the mica tube close to the copper conductors in the coils which are direct connected to the neutral point, where the voltage to earth is in consequence low. The readings obtained on these detectors can be compared with the readings of detectors placed outside the insulating tubes for comparison, and the leads of these detectors can then be cut off where they come out of the stator coil if this appears desirable. The questions arising in connection with self-starting synchronous motors, which are more and more used for driving compressors and similar machinery and for power-factor correction generally, deserve greater attention. In Clause 6 of the Rules the starting torque and the starting current are omitted from the information required with inquiries for such machinery. Clause 93 does not mention that the pressure induced in the rotor windings entirely depends on the pressure applied to the stator terminals when starting. If a certain ratio of this pressure to the full stator voltage has been assumed, this ratio should be given with directions how the test pressures are to be altered in case a different ratio is employed. In Clause 93 (*b*) a rough division is made, in two classes of motors, of exciter pressures above and below 250 volts. As the exciter pressure largely influences the voltage to which the rotor windings are subjected during the starting period, a further grading of test pressures depending on the exciter voltage seems appropriate.

Mr. H. W. Taylor : The essential feature in the latest standardization proposals as indicated by Mr. Everest seems to be a rating based upon a continuous operation and not a rating, as has hitherto been in vogue in Great Britain, which is associated with an overload of 25 per cent for 2 hours. British engineers may find it difficult at first to appreciate this new method of rating, but I think it should be borne in mind that inasmuch as the conditions under which motors are used vary widely, and as the number of cases in which a machine is required to exert a continuous effort are few, any method of rating may be considered to be a nominal one on which the machine may be tested. The function of the commercial engineer is to be familiar with the method of rating and to adopt the motors on his list to the many requirements which he has to face in practice. Nominal bases of ratings have been in vogue for many years for traction and crane motors. I notice that it is proposed to standardize the inlet temperature as 40° C. for British work. It would seem that this figure is rather conservative, but here again the commercial engineer, knowing the basis of rating as regards temperature, will apply his engineering knowledge in the use of the motor, and adapt it to the actual temperature conditions under which it has to operate. With regard to the rating of large machinery (I speak more particularly of large turbo-generators) I believe it will be the custom in the future for purchasers of such machines to specify firstly the actual inlet temperature with which the machines are expected to operate, and secondly that under these conditions the maximum internal temperatures shall not exceed those specified by the I.E.C. Rules. In this way the purchaser will not be expending an unnecessary amount of money on a large machine rated on a standardized inlet temperature which is higher than his own normal conditions. Temperature detectors, however, will be installed in such machines, so that the maximum load on them can be graduated to temperature variations from the normal, as for instance in the height of summer and the depth of winter. With regard to the use of such machines in tropical climates, the use of a wet air filter helps considerably in reducing the initial temperature at which the air enters the machine, by reason of the fact that as the atmospheric temperature rises, increasing quantities of water are completely evaporated into the air as it passes through the filter. Advantage might be taken of this by operating engineers in determining the inlet temperatures at which such machines will normally operate.

Mr. R. Orsettich : One of the advantages of the new rating will be in connection with machines which are not likely to require an overload margin, such as fans, compressors, gas engines and similar machines. In all these cases it will be possible to select a machine which will work at the maximum load required, and the machine will therefore work with a considerably higher efficiency than is usual at present. Apart from this, in the case of alternating-current motors, the power factor will be considerably increased, as the motor will be less likely to work under-loaded

than at present. In par. 23 the standard frequency is stated to be 50 cycles; in view of the fact that two very large industrial districts in this country are supplied with power at 25 cycles, and that similar large supplies are established in Canada and Australia, it seems desirable to consider the adoption of 25 cycles as a second standard frequency. In par. 22 the standard pressures for direct-current motors do not include 550 volts; as on the other hand a large number of motors are continually required for connecting up to traction systems, it seems desirable that this additional pressure should be included. The short-time rating mentioned in par. 38 has given rise to several misunderstandings, since there is no explanation as to how this rating can be used in practice, and it leaves entirely open to the user the time which must elapse between two subsequent periods of work, each of which is equal to the short-time rating. Par. 44 will be amended to cover tropical conditions, and it is proposed that the maximum temperature-rise allowable under such conditions should be 15 degrees C. less than the rise allowed for normal conditions. This appears to be preferable to 10 degrees C. only, in view of the uncertainty of the ambient temperature obtaining under tropical conditions. The wording of Clause 59 as to the duration of temperature tests for machines with continuous rating appears somewhat doubtful, and it is suggested that in order to reduce the duration of the test a temperature gradient should be stated of, say, 1 degree C. per hour, and that when this is reached the test could be finished by making an allowance for the additional temperature. Par. 85 states the frequency of the test pressure; it appears desirable that also the output of the generator used for the pressure test should be given, as this is usually mentioned in most specifications and the absence of any ruling might give rise to abnormal requirements by inspectors. With reference to par. 103 and the following, dealing with the question of name-plates, it appears that it would be necessary to look into this matter further, as the items specified to be given on every name-plate are so exceedingly numerous that it would be difficult to accommodate them on a name-plate of reasonable size. In cases of standard machines these items should be cut down very considerably.

Mr. A. T. Bartlett: A close examination of the specification shows it to be remarkably complete. I am glad to see that there is no mention of the pernicious "flashing" test. I understand that it has been decided to allow no tolerance in the matter of temperature-rise, but I do not agree with this. There may have been very good reasons for fixing a definite final temperature for the various insulating materials and allowing no tolerance, but there are errors of observation in taking temperature runs and in measuring the temperatures which are always present even when such tests are made under laboratory rather than test-room conditions. Two runs of the same machine under conditions as identical as can be arranged will almost invariably give results differing by a degree or two, whether the temperature be taken by thermometer or by the resistance method. Why, therefore, should tolerance be withheld as regards temperature-rises when they are allowed on a number of other points? Mr. Everest pointed out the importance of an international specification as helping international trade; this is a most important point. In Australia, for example, where in pre-war days Continental machines were competing with British machines, a Continental motor was frequently purchased because of its lower price, owing to all motors of a given horse-power being considered to have the same output. The purchaser was not aware that the Continental motor had only 0·85 or even less of the output of the British motor. Another reason for such a specification is that it shall become the *only* specification and in this way free our designers from having to deal with fancy specifications for which the only reason seems often to be a desire to be different. Mr. Everest says that it is to be fully understood that such a specification lays down only test conditions for comparing machines of different manufactures. Such safeguards cannot, for a long time at least, have any effect on the rough treatment which machinery has always to undergo, and the specification is not intended to limit in any way the actual duty a machine has to perform.

Mr. E. J. Kipps: According to Rules No. 36, 38 and 80, motors for intermittent work have a short-time rating of either one hour or 30 minutes for temperature and are to be capable of withstanding on test for 30 seconds a torque 100 per cent in excess of that corresponding to the short-time rating. The difficulty of fixing a time for a continuous run at full load, which shall give the same temperature-rise as the same load on intermittent runs, was evident from the discussion of a paper read before the Institution in 1906 by Mr. C. W. Hill (*Journal I.E.E.*, vol. 36, p. 290). From that it appears that 30 minutes is too long for a continuous run for small motors for loads which they can carry satisfactorily on intermittent work with a running time of 2 or 3 minutes. A short-time rating of 15 minutes appears to cover all cases of crane motors used in practice. For the increased load which a certain motor can carry on a 15-minute rating, as compared with its load on a 30-minute rating, there will be a large increase in the temperature gradient between the copper wires and adjacent parts of the motor, but if the temperature of the armature and field windings is determined from the increase of resistance, there seems no objection to a short-time rating of 15 minutes or even less. Presumably a test under short-rating conditions would not be repeated before the motor had time to cool down to atmospheric temperature. Why is a 15-minute rating not given in the Rules?

Mr. H. Joseph: I should like to endorse the remark of Dr. Kahn that it would be of considerable utility if the Specification in its final form included some standard of efficiency for motors. I would suggest a table of efficiencies for varying sizes of direct-current and alternating-current machines. While endorsing what was said by a previous speaker as to the somewhat cumbersome size of name-plate required to embody all the information enumerated in Clause 103, I think it is most essential that stress should be laid on the necessity for the name-plate to show the rotor current of slip-ring motors as indicated in Section 109 and,

I would add, the field current of all direct-current machines.

Mr. R. G. Jakeman: With regard to the temperature-rises, it is not quite clear to me why commutators and slip-rings are only allowed a maximum temperature of 90° C., while the maximum permissible temperature for mica is 125° C. With regard to field coils, the maximum actual temperature is 105° C., and the maximum temperature by resistance 95° C. The difference takes into account the fact that the mean temperature-rise is measured by resistance, and I should like to know if it allows for the deepest coils met with in practice. A difference of 10 degrees C. seems rather high for the ordinary thin coils on large machines. In the list of particulars to be given when ordering, I notice that rotary converters are omitted.

Mr. A. R. Everest (*in reply*): It is gratifying to note Dr. Kahn's opinion that the explanations and discussion have cleared up many points which were obscure. I will see that his suggestion regarding the free use of explanatory notes in the new edition of the Rules shall reach the proper quarters. Dr. Kahn suggests that the new Rules shall contain standard tests for the verification of guarantees on efficiency and power factor. Some of these matters are already under consideration by the Rating Committee. His remarks regarding the use of embedded temperature detectors are distinctly helpful. With reference to the suggested introduction of embedded temperature detectors within the insulating tube and adjacent to the copper conductors, such methods are now in use for research purposes, but it is doubtful whether they ought ever to be admitted for the commercial tests to which the Standardization Rules essentially apply.

Dr. Kahn suggests that the subject of test pressures for the field windings of synchronous motors as given in Clause 93 needs further consideration and sub-division. The clause in question is the result of much careful consideration both by the B.E.A.M.A. and by the Rating Committee, but any further considered recommendations from the B.E.A.M.A. would receive every attention.

Mr. Taylor recognizes the usefulness of embedded temperature detectors, not only in the initial testing of the machine, but also for giving a continuous indication of the internal temperature during service operation. This is undoubtedly of great practical use in the case of large turbo-generators, particularly as indicating any tendency to change of temperature due to clogging of the ventilating ducts. Several considerations seem to be involved in the suggestion that by utilizing these devices in service, the output of a large turbo-generator may be controlled with reference to the maximum permissible limit of temperature, thus taking advantage of additional output available where the cooling air is below its average temperature, as in winter time, or when the air has been artificially cooled by a wet filter. In the tropical countries to which Mr. Taylor refers, the air when at the highest temperature is frequently at the same time highly saturated with moisture, so that little reduction in the temperature of the cooling air would result at such times from the use of the wet filter. As regards increased output to be obtained in winter time, it must be remembered that the output available from the prime mover is, at most, only a few per cent greater in winter than in summer, therefore it is not easy to see how any larger increase in output of the generator made possible by abnormally low temperature could be utilized.

Mr. Orsettich points out that by giving better attention to the selection of a motor with respect to duty required, improvement in efficiency and power factor will result; this is certainly desirable. He suggests that 25 cycles should be recognized as a standard frequency; this point will no doubt be further considered by the Electricity Commissioners. Regarding the short-time rating, this is a rating established for test purposes in which a specified load is applied to a machine for a specified time, starting cold. Machines rated in this way are employed particularly on intermittent service, such as cranes, hoists, etc., and it is obviously necessary that for any particular service a short-time rating shall be selected which is thermally equivalent (i.e. gives the same temperature-rise as the intermittent load of service conditions). Obviously, in service the machine can only carry its full load for a time equal to that in the rating, when the subsequent period of rest is long enough for it to cool down to air temperature before the load is again applied. When in service the load is applied at more frequent intervals the duration of the load, or its magnitude, or both, must be less than those specified in the test rating in order that the final result, after repeated applications, shall be thermally equivalent. When a customer does not know from past experience which rating is suited to his particular service, the engineer-salesman should be able to advise. Possibly some explanatory note which would be of assistance might be introduced in the Rules. Mr. Orsettich's recommendation that the permissible temperature-rise of the machine should be reduced 15 degrees C. when intended for tropical conditions agrees, I think, with the general opinion. Regarding the duration of temperature tests for machines with continuous rating, earlier Rules provided that the test should be continued until the rate of increase of temperature did not exceed 1 degree per hour. But the length of time required to attain this condition, and the amount of difference still existing from the ultimate constant temperature condition, both depend upon the thermal time-constant of the machine. Thus, in a large oil-filled transformer, a heat run at rated load for more than 24 hours would be required to reach the 1 degree per hour condition, and even then the temperature would be several degrees short of its actual steady value. The present Rule, Clause 59, assumes that the shape of the temperature curve will be plotted and its ultimate value thereby predicted. It is possible that some note explanatory to the Rule might be of assistance in this matter. Mr. Orsettich suggests that Clause 85 should specify a minimum output for the generating plant employed in making high-pressure tests. The reply is that any testing equipment which is too small to maintain the test-pressure at its full value for one minute when applied to the apparatus under test, as required by the Rules, Clauses 86 and 87, is insufficient for the purpose. Nothing is gained by specifying a minimum capacity larger

than that required to meet the conditions specified in the Rule.

I am glad to hear Mr. Bartlett's remarks regarding the assistance which may be expected in international trade by the adoption of an internationally agreed basis of test rating. He considers that the temperature limits should be allowed tolerance to cover errors of observation and other uncertainties as in the case of the measurement of other characteristics. Regarding this, it may be pointed out that the use of a tolerance in connection with a value always carries with it a "resultant maximum." The temperature limits given in the International Rules are expressly defined as being themselves the "maximum values"; hence, if a tolerance is to be employed it must be based on such lower value that with the tolerance added the "maximum" is not exceeded.

Mr. Kipps refers again to the short-time ratings and suggests that it would be desirable to add a 15-minute rating to the standards recognized. If the makers agree as to its desirability there should be little difficulty with regard to its recognition.

Mr. Joseph would like to see in the Rules a table of standard efficiencies for various sizes of alternating-current and direct-current machines. This is a matter which is largely in the hands of the makers themselves. If they were to agree upon the values of the efficiency suitable for the purpose, such lists might be usefully included in the Rules.

Mr. Jakeman asks why the limiting temperature for commutators and slip-rings is lower than that allowed for the mica insulation between the segments of a commutator. The reply is that the temperature of the commutator has to be considered not only as regards its effect upon the mica, but upon the insulation of the adjacent windings, soldered joints, and upon the brushes and commutation generally. It is expected that the revised British Rules will embody a clause recently introduced into the International Rules, which permits commutator temperatures higher than the usual limits, subject to special guarantees which are to be given regarding the performance. As regards Mr. Jakeman's comments in connection with the temperature limits allowed for field coils by resistance measurement and the probable hottest internal temperatures, it must be pointed out that the British Rules agree with the I.E.C. Rules in defining the working limits in terms of the "observable" temperatures as measured by the resistance of the windings as a whole. The remarks in the Appendix regarding the hottest internal temperatures are not intended as Rules, but as information indicating the general relationship between the working limits assigned in the Rules and the probable internal temperatures.

Several speakers have pointed out that the section dealing with information to be given when ordering is not at present complete. This is fully realized. As regards information to be given on the name-plates, opinions evidently differ, some considering that more should be given, while others consider there is already too much demanded.

DISCUSSION ON "TRANSFORMERS FOR ELECTRIC FURNACES."*

North-Eastern Centre, at Newcastle, 9 February, 1920.

Mr. V. Stobie: The author seems to be afraid of the breakdown of transformers due to tappings. He has, of course, had considerable experience with transformers and will doubtless be aware of more breakdowns than I have heard of due to tappings, but I think his suggested remedies are not quite the ideals which he considers them to be. I have not had any breakdowns on furnace transformers due to tappings, and as the main difficulty, according to the paper, seems to be that workmen may not sufficiently insulate such tappings, my advice would be that no tappings should be insulated except in the presence of a qualified person in charge of the work. As the author's alternatives to tappings are very costly, I consider the extra cost of such supervision to be an exceedingly good investment. Such breakdowns as I have experienced have been mainly at the rounded-off corners of the oblong high-tension windings of shell-type transformers, and I believe have mainly been due to abrasion of the windings resulting from the repeated reversals of mechanical stresses in the transformers after shrinkage of the insulation. The abrasion of the insulation is, I consider, a far more important question than the mechanical stresses themselves, to which reference is made on page 211 of the paper. I have always advocated the use of plenty of reactance in furnace transformers rather than the cutting down of the reactance of the transformers and the provision of reactance in the furnace leads. I recall an instance where I specified quite a high reactance for some transformers, and on finding great local heating in the transformer windings I had the transformers opened out. In order to get the high reactance, the transformer makers had sandwiched reactance iron amongst the windings. When considering some other point in the design of that same transformer, possibly in some office at the other end of the maker's works, the transformer was arranged to have oil ducts much too small for efficient ventilation. It seems strange that in such cases transformer makers should adopt such a mixture of ideas instead of obtaining the required reactance by increasing the size of the ventilating ducts. The heating which arose in the special reactance iron mentioned was such as to char the high-tension insulation, and the transformer had to be rewound. In regard to the future of large furnaces, I am much more optimistic than the author, and I can see no difficulty whatever in increasing the size of a single unit up to any capacity that could be worked metallurgically in a steel-works. There is no need to adopt fanciful polyphase currents for large furnaces. Instead of having 4, 6, 8, 10, etc., phases as the furnaces increase in size, all that is necessary is to have two two-phase, two three-phase, three three-phase, and so on, keeping down the complexity of the connections and multiplying the single unit electrically.

* Paper by Mr J. L. Thompson (see pages 201 and 301).

Mr. H. W. Clothier: With reference to the danger of short-circuits between the interleaved low-pressure conductors, I suggest that there would be less risk if the edge of the conductors of one pole were stepped a small amount, say $\frac{1}{4}$ inch, below the edge of the other conductors. The proper remedy for the failure of insulation of switchgear and transformer terminals is the careful enclosure in metal, and sealing in compound or oil, of all conductors and surfaces of insulators. At all situations there is a risk of arcing across air spaces owing to inconstancy in the insulation of air and the effect of acid-laden air and moisture on exposed insulating surfaces. In furnace equipments this risk is particularly prevalent, as the air is frequently impure. Moreover, owing to the inductive nature of the load, and sometimes to the peculiar connection required for boosting and regulating, unexpectedly high-potential stresses occur in places during switching operations. These momentary shock stresses are more easily resisted under oil or compound than in air.

Mr. S. A. Stigant: I was very pleased to see that reinforcement between turns is advocated by the author, especially where tappings are brought out, which of course applies whether the tappings are brought out from the ends or from the centre of the winding. In certain directions the tendency seems to be rather to discount the necessity for this reinforcement when tappings are situated at the centre of the windings. While it cannot but be agreed that tappings at the ends of the windings may be subjected to heavier voltage shocks than those in the centre, there still remains the possibility of obtaining abnormal voltage stresses, by the mechanism of wave reflection, on open-ended tappings even when these are situated in the centre of the windings. To my own knowledge one case at least of such a breakdown has occurred on a large transformer in this district, and I believe that quite an appreciable amount of this sort of trouble has been experienced in the States. There are, of course, several methods adopted for minimizing or eliminating the trouble, and these consist in principle either of paralleling the unused tappings or of entirely disconnecting those parts of the windings which are temporarily not required. With regard to the ratio of copper to iron loss, the author and I have already crossed swords over this matter and, while the influence of this ratio on the efficiency and cost of open-circuit losses is not important in furnace transformers, it has a very serious effect on the maximum permissible overload and temperature rise to which the transformer may be subjected. With a high copper to iron loss ratio, and for a given maximum temperature rise, the permissible maximum overloads are very small, while, conversely, with a low ratio appreciable overloads may be obtained without an undue increase in temperature rise. As an instance of this, if a transformer is designed to give a temperature

rise of 40 degrees C. at normal full load with a copper to iron loss ratio of 3, a 50 per cent overload will produce a temperature rise of approximately 88 degrees C., whereas with a ratio of 0·33 the same overload will only produce a temperature rise of approximately 53 degrees C., the ratios quoted being those which occur at normal full load. Experience in this district tends to show that bracing, to avoid destruction of windings due to a fault between turns, is not so much an impractical possibility as totally unnecessary. The present-day automatic protective devices usually employed disconnect the faulty transformer during the period in which the fault is local only, and therefore confine it to the particular coil in which the short-circuit occurs; and it is very infrequent that other coils become distorted in any way due to such a fault. The life of the transformer is intimately bound up with a proper design of the internal oil-circulating system, and while the author advocates the provision of numerous ventilating ducts it should be borne in mind that a large number should not be sought for at the expense of the dimensions of the ducts. It is much more important to provide a smaller number of sufficiently wide ducts of, say, not less than $\frac{1}{2}$ inch in width, so that one gets a substantial body of oil in circulation, rather than a larger number of narrow ducts which are always liable to facilitate sludging. This, of course, does not mean that one should go to extremes. For instance, in shell-type transformers it is not desirable to concentrate the whole of the winding in a few thick coils with very wide ducts between. A case recently occurred of the failure of a single-phase transformer from a short-circuit between turns, and upon dismantling the transformer it was found that practically the whole of the high-tension winding had its insulation completely charred, so much so, that it was impossible to remove the coils without them falling to pieces. This condition was entirely due to an inferior design of the internal oil-circulating system, and it is worthy of note that the only overload carried by the transformer was about 15 per cent for a week or so. The author states that only the high-pressure leads required should be brought out of the case, the remainder being maintained under oil-level. A large number of transformers have been supplied for service in this district, and experience shows that there is no reason why all leads should not be brought outside the case though, as stated in the paper, the line leads should be brought through separate insulators. In fact, Fig. 2 shows the type of high-tension terminal through the case which is referred to, and although slight troubles have been experienced at various times they have on the whole been negligible. From an operation point of view one of the main disadvantages of the rectangular shell-type transformer where the plates are built up separately round the coils, is that if the transformer breaks down it has to be returned to the manufacturers for repair, entailing delay and additional expense. Admittedly this aspect is of more importance with ordinary power transformers, but it might also apply, in perhaps a lesser degree, to furnace transformers. Core-type transformers can usually be repaired on site, it being only necessary to obtain new high-tension coils (on which faults more often occur) from the makers. For furnace transformers carrying low-tension currents of the order of 5,000 amperes this practice might still be adhered to. Regarding mechanical stresses, the author states that it is not so much the influence of the magnitude of the forces which are shown to be relatively small, as the frequency with which they occur. It should be pointed out that in this connection special attention should be given to providing adequately wide oil ducts as previously referred to. If the heat generated in the windings is not dissipated properly, or if the transformer is subject to heavy overloads, the insulation may become very brittle so that wholesale flaking off may occur in the event of any movement between adjacent conductors, such as is liable to take place when switching in a transformer or at the moment of an external short-circuit, and a serious local short-circuit will result. In view of the high temperatures (due to their particular location) to which the transformers are liable to be subjected,

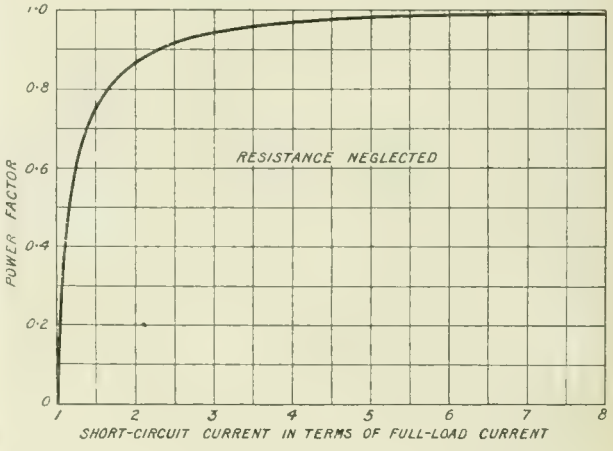


FIG. F.

I think somewhat thicker insulation might be placed on all turns, though, of course, this would necessitate possibly a slightly larger core and more expensive transformers. This would give the insulation more "body" and enable it better to withstand higher temperatures. Obviously the thickness should not be increased to such an extent as to produce a higher temperature gradient in the windings. Here again it is not suggested that extreme measures should be taken. The author's figures regarding the influence of power factor on the mechanical forces are particularly illuminating, as this aspect is quite often overlooked. Fig. F herewith shows the relation between power factor and short-circuit current. From a study of this diagram it will be seen that even a low power factor has its compensation, and although this occurs only over certain limited periods it does so when most required.

Mr. G. E. Taylor also took part in the discussion. The substance of his remarks will be found on page 217 in the discussion before the Institution.

Mr. J. L. Thompson (*in reply*): Mr. Stobie has hardly interpreted correctly the author's remarks as regards tappings. The trouble experienced has not

been at the actual tapping points on the winding, but has been due to their position at the end of the winding, causing an auto-transformer effect. Also, failure of the switchgear which is connected to these tappings has been a source of trouble. If no tappings were used, the above causes of trouble or sources of weakness would be eliminated. The author agrees that abrasion of the insulation due to imperfect clamping, etc., has been the cause of trouble. Shrinkage under normal conditions in a shell-type transformer is non-existent, but if the low-tension bars vibrate due to heavy oscillating loads, abrasion of insulation may result. The use of magnetic shunts for obtaining high reactance values is quite a sound proposition, but care must be taken in such designs, as local heating may take place with an incorrect design. This is probably what occurred in the case quoted by Mr. Stobie. The latter's suggestion for large units is interesting, but in these cases a large number of electrodes would be required, necessitating special attention to the roof structure of the furnace.

Mr. Clothier's suggestion of stepping the low-pressure bars is ingenious, but hardly necessary. This stepping would increase the losses in the low-pressure lay-out and also the impedance. For instance, if 4-inch bars were used and stepped $\frac{1}{4}$ inch, the impedance of the lay-out would be increased $6\frac{1}{2}$ per cent. Mr. Clothier's remarks regarding totally enclosed leads were fully dealt with in the author's reply to the London discussion (page 220).

Mr. Stigant's remarks about insulation of tappings are in part correct, but the tappings do not require the same reinforcement as end turns. The insulation here is required from the point of view of mechanical safety, rather than for safeguard against surge voltages. The question of ventilation of the winding is very important and experience on this question is the safest teacher. If the temperature can be maintained uniform throughout the windings, the problem of ventilation is solved, and the only way to do this is to have numerous oil ducts distributed evenly throughout the winding. Mr. Stigant's suggestion of $\frac{1}{2}$-inch ducts cannot be justified, except for large units having long oil ducts. The question of sludging is, in most cases, non-existent if good oil be used. The author does not state that all leads should not be brought out of the transformer case, but owing to the conditions of service of furnace transformers it is undesirable to bring out more than are absolutely required. The question of repair has been dealt with by the author in his reply to Dr. Kahn (page 305). If the insulation used were heavier throughout, the transformer would have a longer life if the oil ducts were not sacrificed in consequence, but of necessity the cost would be heavier.

North-Western Centre, at Manchester, 27 January, 1920.

Mr. H. G. Furlong: I agree generally with the author's opening remarks, but I wish to protest against the comparison which he makes between the core type and the shell type on pages 205 and 206. Some of the disadvantages attributed to the core type are more imaginary than real, and some of the advantages claimed for the shell type are equally applicable to the core type. In the latter the coils surrounding the core are no more liable to damage during manufacture than they are in the shell type, because the same precautions can be taken. They may be liable to damage during shipment, or during unpacking by the customer in cases where the transformer and tank are packed separately, but as the majority of transformers are dispatched complete in their tanks this danger is almost entirely eliminated. The unequal lengths of the low-pressure leads, the number of heavy joints, and the question of ventilating ducts are almost entirely matters of design. If the core-type transformer is placed in a vertical position in its tank, as is the standard practice with power transformers, there is a difficulty in arranging the low-pressure leads all the same length, but there is no reason at all why the core-type transformer should not be placed in a horizontal position in its tank and thus overcome these difficulties. At the same time this will get over the objection which the author has with regard to cooling by radial oil ducts. I agree with him that they are of very little use if the transformer is in a vertical position; but so far as cooling is concerned there is no necessity to place the transformer in a horizontal position, because ample ducts can be left between the inside circumference of the coil and the core of a greater width than is possible with the shell type. Coupled with the radial duct a much better circulation of oil will be obtained. The author states that there is a difficulty in making joints on core-type transformers. The last two slides shown on the screen illustrated coils wound in a continuous length. Those coils are suitable either for the core-type transformer or for a circular shell type. The same machine is capable of winding coils for a rectangular shell-type transformer, and both circular and rectangular turns can be wound in one continuous length, so that the difficulty of joints is entirely overcome. I should like the author to explain more explicitly the difference between the two types, in losses under load due to the direction in which the leakage flux between the primary and secondary windings cuts the punchings. The only difference that I can see is that in Fig. 3 an end view of a core-type transformer is shown, so that the field does actually cut the punchings at a right angle; but if the core were turned so that it is at right angles to the other two sides of the core the leakage flux will cut the punchings in a parallel direction. Fig. 4 shows an approximately reverse position of the transformer to Fig. 3. I agree that on the rectangular shell type there is a greater length of core on which the leakage flux would cut the punching in a direction parallel to the laminations, but at the same time there is a greater amount of iron in the rectangular shell type than in the core type, so personally I do not consider, so far as the losses due to leakage flux are concerned, there is any difference between the two types. The author also states, regarding core-type transformers, that if voltage varia-

tion is required by means of high-pressure tappings the low-pressure coils adjacent to the cut-out high-pressure coils will carry little or no load due to their increased reactance. Regarding the shell-type transformers he states: "The central position of the high-pressure tappings reduces to a minimum the unbalancing of the load in the low-pressure coils." Surely he does not design core-type transformers for furnace work with high-pressure tappings unless they are put in the centre of the winding so as not to interfere with the reinforced turns, or materially affect the balance of load in the low-pressure parallel coils. The same arrangement can be made on the core type as on the shell type. On page 205 the author says with reference to core-type transformers: "A strong and good-looking piece of apparatus can be made with this construction, provided good workmanship is available." I should like to add to that and say: "Can be made with either core-type or shell-type transformers, provided good design and workmanship are available." One is useless without the other. I can quite understand the author's remarks if he was referring to such a transformer as is shown in Fig. 3. It is quite impossible in that particular transformer to get any adequate cooling surface. Circulation of oil is impossible, due to the faulty design of the yoke clamps. The oil which is in the inside between the coils and the core cannot get away, and the result is that the coils would very soon heat up and burn out. These remarks apply equally well whether the transformer is for use on furnace work, power work or lighting work. I presume the illustration has been included to show the core type in its worse form. I do not believe for one moment the author intended to represent Fig. 3 as a really typical design. With regard to tappings, I am in entire agreement with the author. These should certainly be placed so as not to affect the end-turn reinforcement, the distribution of load in the low-pressure conductors to any great extent or, likewise, the reactance. If tappings can be omitted the transformer will then be very much more reliable. Boosters or induction regulators could be used for regulating the voltage, and if these break down the main transformer can still be used for working the furnace as the author suggests. The author showed some photographs on the screen with tappings similar to those in Fig. 2. The high-pressure leads and tappings appear to be brought through single bushing and tied together with string. I should imagine with this type of construction a considerable amount of trouble would be caused by flash-overs between the tappings due to surges. What experience has the author had in connection with this type and does he not find it more advantageous to keep the tappings entirely under oil? The author's patent for obtaining half turns is very ingenious, but I should imagine that considerable difficulty would be experienced due to this extra length of low-pressure lead which is necessary to bring the half turn from the bottom of the transformer through the top of the tank. I should also imagine that a considerable amount of additional reactance would be caused and also additional losses, due to the half turn encircling the bottom cast-iron base and the top casting. Another trouble would be that the heavy leads will have to be jointed at the bottom of the transformer where it is almost impossible to inspect them. If, however, these objections could be overcome his patent would make it possible in certain cases to obtain very much more economical proportions of material in the shell-type transformer. Furnace lay-outs are not always scientifically designed. This work is usually in the hands of the furnace manufacturers, with the result that there are very few (if any) lay-outs in this country that could not be considerably improved. It would be a considerable advantage if manufacturers of transformers and furnaces could get together and discuss these points, especially as in a great many instances the buyer of the furnace insists upon the furnace and the transformer being placed in a given spot, without any consideration being given as to whether the position is satisfactory or not.

Professor Miles Walker: The author has referred to the reactance of the leads to the transformers. That is a matter which has claimed the attention of electrical furnace engineers in recent times. A great deal of trouble has arisen through careless laying out originally, and very often it has been difficult to reduce the reactance to the right amount. In this connection I believe that many engineers who are dealing with the matter do not fully appreciate the fact that we can reduce the reactance just as well by increasing the diameter of the leads as by reducing the area enclosed by them. In cases where it is impossible to reduce the area enclosed we can sometimes make a good lay-out by increasing the diameter of the leads. In the ordinary way if we have a wide strip, say 4 inches or 6 inches wide, the copper in the centre is of no use at all; all the current goes down about $\frac{1}{2}$ inch at each side. But we can increase the size of the leads by making a sort of cage built up of a lot of cables in parallel (see Fig. G). In this sketch the individual conductors are shown quite thin so that

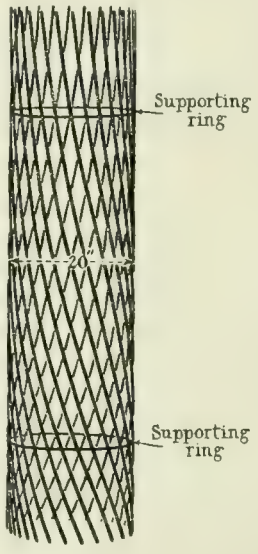


FIG. G.

the "cage" construction can be seen. In practice the cables have a diameter almost equal to the distances between centres. As a matter of fact we can get nearly as much conductivity from a 50-cycle cable with an arrangement of that kind as we can with direct current. In practice many electric furnaces use very much more copper than is needed, because a large proportion of the copper is not carrying any current at all, or it may be carrying current in the wrong direction. The author raises the question of the increase of voltage in the transformer. This is not always a matter that can be done. Suppose we have decided to have a certain power factor, say 0·8; we might have 80 volts between electrodes, 60 volts for the reactive drop, and 100 volts total. It sometimes happens that the pressure across the arc of the furnace cannot be indefinitely increased without bringing about undesirable conditions in the furnace. When the reactive drop is too great, the first step is to ascertain to how high a point we can raise the voltage between electrodes. That point being settled, the transformer should be arranged to give this maximum voltage, thus reducing the current and the reactive drop to the minimum. There is another matter that I have not seen mentioned in connection with electric furnaces; it is in connection with the power factor. The low power factor on the low-tension side of the furnace is not entirely due to the reactance of the leads. The resistance of the arc decreases during each half-cycle, so that apart from reactance the current lags behind the pressure. I have found by wattmeter measurements that the power factor is lower than can be accounted for by the known reactance of the circuit. The effect may be said to be due to "delayed conductance."

Mr. J. Frith: I am rather surprised that the author does not deal more with the switchgear

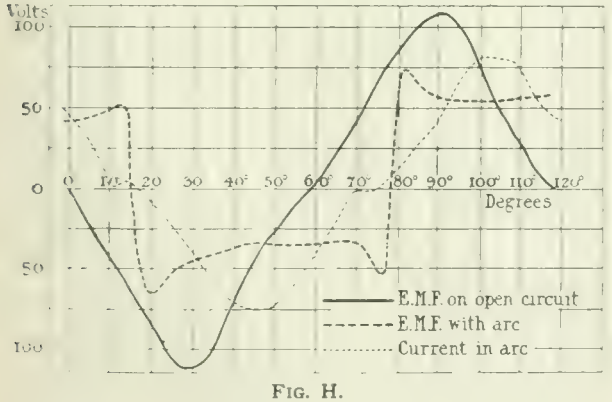


FIG. H.

controlling furnace transformers. It would seen that these big transformers are very much at the mercy of the switchgear, and that the failure of a transformer is often, at any rate by its designer, put down to the failure of the switchgear controlling it. The other point that I wanted to raise has been partially dealt with by Professor Walker. It is the effect of a pure arc furnace on the wave-form. Fig. H herewith shows first the E.M.F. wave of an alternator on open circuit and also the E.M.F. and current waves of the same alternator feeding an arc. Such alterations to the wave-form cannot but have some effect on the design and working of the transformer, as wave-forms are transmitted through a transformer with very little alteration.

Mr. A. G. Ellis: It is rather a pity that the paper is more or less confined to one class of furnace, that is the steel furnace, and almost to one type of transformer. When it is remembered that, as stated on page 201, we have only been at this business of electric furnaces for about 10 years, I think it will be realized that the manufacturers of this apparatus, and of the electrical gear connected therewith, have had rather a strenuous time of development. We have had to buy our experience sometimes under very difficult conditions. Now that the war conditions have finished, and we have got most of our troubles with electrical equipment of electric furnaces behind us, there is rather a lull in the demand for this apparatus, so that we cannot apply to the extent that we really desire the experience we have gained. At item (5) on page 202 the author refers to "Failure of transformers due to bad housing, unskilled operation and heavy overloads." This question is largely—I would say almost entirely—in the hands of the maker of the furnace or the engineer who puts down the plant. During the development of the electric furnace the matter of fixing the capacity was largely a matter of trial and error and the actual capacity required for the transformers was a matter of uncertainty, which resulted often in their being called upon to support much heavier continuous loads than were originally specified, or for which they were designed. The result of this has been that the transformer has in certain cases suffered from unfair overloading, and to mitigate this certain engineers have specified the current densities to be used in the windings in addition to the rated output. This is not the most satisfactory way of ensuring that the transformer will be sufficiently liberally rated. It may, in fact, result in a worse piece of apparatus than the buyer would really get if he simply said what he wanted and left it to the manufacturer to make the apparatus to comply with the specified requirements in his own way. I should like, in connection with this question of rating and overloads, to put in a plea for the British standard rating, especially for this class of apparatus. As is commonly known, the British standard basis for transformer rating is 50 degrees C. rise in oil. It is often the custom to specify a low temperature rise on "normal" load and a high continuous overload capacity. The more logical way is to include the continuous overload in the normal rating and specify this as the maximum continuous rating on British standard temperature rise. If we could only get down to this standard rating, it would be to the benefit both of the engineers who put down plant and of the manufacturers who make it. The author says: "The requirement of steel furnaces may be for single-, two- or three-phase supply," but he deals almost exclusively with single-phase transformers, although later on the question of core type versus shell type is raised. It is sometimes claimed that one can get better efficiency with one or other of these types of transformer, but there is really very little in it.

Also there is little difference as regards size and weight of the two types for the same output, as is shown by comparing Figs. 1 and 2 in the paper. I should like to touch upon the question of increasing the capacity of the furnace (page 207). This is a matter which exercises the furnace makers very much. To increase the number of phases unduly is rather a dangerous thing, because the greater the number of phases the more complicated the switchgear becomes and the more liable the whole apparatus is to breakdowns. I do not think this is going entirely in the right direction. On page 207 the author refers to a "straight transformer"; will he please explain what he means by that? I should like to criticize the half-turn arrangement shown in Fig. 5. The difficulties associated with this design are chiefly mechanical ones relating to the bringing out of a connection for a heavy current at the half turn. Regarding the system of low-tension voltage regulation by means of a low-tension booster transformer built in above the main transformer, the principal limitation of this arrangement is the restriction in headroom. In Fig. 6 is illustrated a transformer of this type which stands 11 ft. 9 in. high for only 1,250 k.v.a. output. For the maximum output of 7,920 k.v.a. mentioned on page 207 this construction would on this account be out of the question. The question of low-tension leads between transformers and furnace has, I believe, given rise to more trouble in these installations than any other factor. I wish the author had shown a few general plans of furnace and transformer installations, illustrating where the difficulties occur, what is a good lay-out, and what is not a good lay-out. I was rather attracted by Professor Walker's suggestion for getting over the current-distribution trouble in heavy current leads, but has such an arrangement actually been made? If so, I should very much like to see the mechanical arrangement for bracing all these cables and holding them for a length of possibly 20 or 30 feet between the transformer and the furnace. On the question of leads Mr. Furlong remarked that transformer manufacturers and furnace builders should get together to discuss these points. They do, but unfortunately it generally is only after the trouble has occurred.

Mr. H. A. Ratcliff: Apart from questions of design my views are generally in agreement with the opinions expressed in the paper; but I am more immediately concerned with the supply aspect of the matter, and in that connection there are one or two points in the paper which attract my attention. On page 202 the author speaks of "the supply company's capability of dealing with sudden and heavy loads," whatever that may mean. It is only right that a supply authority should have the power of imposing such restrictions as will ensure that the supply to other consumers will not be interfered with by the operations of a furnace. Presumably any authority which undertook the supply to such a furnace would be able to deal with the 1·6 and 2·3 times normal load (referred to by the author on page 211), but I do not think they should be expected to deal with the enormous surges and current-rushes which may occur when switching in these large furnace transformers unless the necessary precautions are taken, nor with the effects of short-circuits on secondary terminals and switchgear. In this connection I presume that the switchgear controlling the boosting transformer shown in Fig. 8 is effectively interlocked, for otherwise its operation would be attended with considerable risk. On page 201 the author refers to failure of insulation of switchgear and transformer terminals, etc. No doubt he is familiar with the cause of some of the failures, which may have been due to the auto-transformer effect referred to, but I am inclined to think that in many cases they have been caused by the surges due to the nature of the furnace load, or from the conditions which arise when these large transformers are switched into circuit. The nature of these surges was dealt with very thoroughly by Dr. Marchant in a paper read before the Institution two years ago (*Journal I.E.E.*, 1918, vol. 56, p. 445) and I have had some actual experience of what occurs, particularly when switching in a transformer of considerable k.v.a. capacity such as is used in furnace work. I have seen evidence of sparks having flashed across distances of 4 or 5 inches, which shows that the strains on switchgear and the end turns of transformer windings are very real. A case occurred quite recently when switching in a transformer of this description—not a furnace transformer but an equally large one—the surge caused the switchgear to flash over; the sparks were of the order of 3 inches long and the resulting arcs caused the complete destruction of the high-tension switches in the substation concerned. Fortunately experience has also shown that in most cases the cure for this particular trouble is a comparatively simple one, as it has been found that the addition of auxiliary contacts to the switches, with charging resistances inserted between the main and the auxiliary contacts, enables the transformer to build up its magnetism of correct polarity and so avoid a heavy rush of current when the main contacts close. It is also an interesting fact that it is possible for current-rushes of this nature to take place when switching out a transformer. I can only suppose that it is due to the effect of chattering contacts on the switches, since such intermittent contact is frequently the cause of abnormal effects. The author refers to the effect of external reactances inserted in the high-pressure supply mains. I would suggest that they should be fixed as near as possible to the cable head, and preferably immediately after the isolating links; for otherwise the result will merely be that the main high-tension switches will act as spark-gaps and the current transformers as choke coils. I have recently seen the result of a current transformer acting as a choke coil. The normal pressure between the transformer winding and earth would be about 3,800 volts, but the spark resulting from the surge flashed through a thickness of insulation and then over an air-gap of sufficient extent to indicate that the momentary pressure was more nearly of the order of 100,000 volts. I consider that troubles of this nature would be minimized to some extent by an increase in the supply pressure, for the ratio of surge voltage to working voltage would be lower and the switchgear and other apparatus would be constructed to withstand much higher pressures. Extra-high-pressure cables are

also, I think, capable of absorbing these shocks to some extent, and there is another possibility which is rather interesting and which wants looking into rather more thoroughly. It may be found that the relatively high dielectric loss in extra-high-tension cables will tend to damp down appreciably any oscillatory effect between the capacity of the cables and the inductive portions of the circuit, or in other words the energy of the oscillations will be partly absorbed in the dielectric of the cables; but that of course can only be proved by future experience. I was interested in the author's reference to the operating power factor of furnace loads, as I have made one or two attempts myself at estimating and measuring the power factor of such loads and have both obtained figures and seen figures obtained by others, but I am very sceptical indeed as to whether they have any real value or meaning. In the case of a three-phase furnace load, for instance, the pressures, currents, and phase angles are very rarely, if ever, exactly balanced; there is always some disturbing factor, and with ordinary instruments that makes the measurement of the equivalent three-phase power factor rather a difficult matter. Some time ago I had an opportunity of inspecting oscillograph records of currents and pressures in furnace circuits, and it is really no exaggeration to describe them as extraordinary. Naturally one expects the combination of an unstable arc conductance with the variable permeability of a magnetic circuit to give some rather unusual wave-forms, but hardly so extraordinary as the ones in question, and I should like to ask the author whether such abnormal wave-forms are incidental to the furnace circuit only and if they are damped out to any great extent by the transformer, because if they are not there is a very considerable doubt as to the accuracy of the indications and registrations of commercial measuring instruments installed in the primary circuit, particularly instruments of the induction type. The matter is therefore one of considerable importance. The description on page 211 of the precautions to be taken in laying out a transformer installation is extremely interesting and very complete. It is really surprising how frequently the necessity for these precautions is not appreciated as it should be. I have known several instances of constructional ironwork getting excessively hot due to the proximity of conductors carrying currents of a very much lower order than the currents dealt with in the paper. In one particular case, iron bolts in constructional woodwork supporting conductors carrying heavy currents became sufficiently hot to fire the woodwork. When inspecting a large transformer recently I was surprised to find that the clamps holding the low-tension terminal conductors formed a complete magnetic ring round each separate conductor; of course it was a case of pure oversight, but serves to illustrate how easy it is even for a transformer maker himself sometimes to overlook these little points.

Mr. F. E. Hill: As the engineering of a furnace installation is almost invariably entrusted to the furnace manufacturer, I think it is fortunate that this paper points out the difficulties with which the transformer designer is faced. It is only natural that the furnace manufacturer gives particular attention to the furnace and, in specifying his requirements for the transformer, has in mind more the ideal conditions for the furnace than the difficulties of transformer design. In addition, if any necessity arises for a reduction in the cost of the installation, the transformer, being the most costly of the auxiliary apparatus, is reduced in capacity and consequently in cost. It is time, in order to ensure the satisfactory operation of the large equipments suggested, that there should be close co-operation between the furnace and transformer manufacturers. The author has dealt with transformers designed for working from supply systems of a maximum voltage of 22,000. In view of the number of schemes using higher pressures which are being developed in this country, and the still higher pressures in use on the Continent, the scope of the paper might have been wider in this direction with considerable advantage. I think it will be found that where two-phase furnaces of small capacity are supplied from a high-voltage three-phase system and require a Scott transformer group, it will be most satisfactory to install a straight transformer stepping down to an intermediate pressure of about 5,000 volts, and a Scott group with the necessary tappings stepping down further to the furnace voltage. The extra cost of using two transformer groups will be counterbalanced by the reduction in price of the switchgear and by the greater factor of safety obtained by the tappings being on the intermediate voltage winding. Referring to Mr. Ellis's remarks about rating, I have on one occasion seen a specification calling for a 2,000-k.v.a. 25-cycle furnace transformer with a temperature rise after continuous full-load run of 45 degrees C., and of 55 degrees C. after continuous overload of 50 per cent. These figures correspond to a ratio of iron loss to copper loss of 4·6 to 1, which is absurd. The curves given in Fig. 9 are very interesting, but their utility has been limited by basing them on transformers having a fixed ratio of minimum and maximum low-tension voltages. The cost and weight should have been plotted against the equivalent kilovolt-amperes and the method of calculating the equivalent kilovolt-amperes given. At first sight it also appears extraordinary that a voltage ratio of 1·31 and not 1·3 has been used, but as the example on page 213 is based on a transformer with low voltages of 65, 75, and 85, I presume that this is the reason for the selection of this ratio. Comparing the cost of furnace transformers as given in Fig. 9 with the cost of power transformers of similar equivalent kilovolt-amperes as given in the author's paper on "Large Power Transformers," it appears that furnace transformers are about 30 per cent more expensive. I should like the author's opinion on this, as possibly the curves are based on manufacturing costs at different periods.

Mr. H. S. Binns: The paper generally and the broad principles put forward will be endorsed by those who have had experience with this type of apparatus. The author has rightly emphasized the importance of substantial construction and sound design in transformers used for electric furnaces. Considerable trouble has arisen owing to lack of appreciation of this in many cases, but considerably more trouble has arisen owing to electric furnaces being manipulated by staffs with

very slight knowledge of the electrical side of the apparatus. For example, a furnace built for 30 cwt. may be capable of holding 3 tons, but so to load it and, then, attempt to speed up the process by overloading the transformers must result in serious overheating and, finally, breakdown. The failure when it occurs is almost invariably attributed to bad design or careless workmanship on the part of the transformer makers. Cases of this sort are more common than might be thought. Sheffield steel manufacturers are very prone to this fault. I think we shall all be in agreement with the author on the subject of electrical characteristics, as given on page 202. This also applies generally to the mechanical characteristics, although I would suggest to the author that it is preferable for all high-tension leads connected to the transformers to be taken through suitable bushings into the transformer cases and connections made under oil, wherever the designs allow this to be done. The increase in cross-section of the low-tension leads above oil level, as mentioned by the author, does not appear to me to be either necessary or desirable: unnecessary, as the leads above oil level are relatively short, and the copper is a sufficiently good conductor of heat to prevent injurious heating at this point, assuming reasonable current densities; undesirable, as it tends to extra joints in the copper or manipulation which may weaken it mechanically. The distance between the lower side of the furnace leads and the oil level is seldom more than 6 inches. In referring to locations and operation the author gives figures which I would increase. A minimum distance when stated as satisfactory by the manufacturer tends to become the maximum when space is being allocated by the user. I would suggest a minimum of 2 ft. 6 in. for transformers of 500 k.v.a. and upwards. This will allow the transformers to be inspected and cleaned down; the lower figure will not. The author goes into the old, but ever new, question of core versus shell-type transformers. Some of the core types shown on the screen this evening are in all but name of shell design, and some of the shell type are of core design. I cannot agree that the core type must of necessity suffer from the defects mentioned by the author. Further, I cannot agree that the shell type suffers from the disadvantages given as hereditary defects. It is all a question of design. A transformer designer should approach each particular problem with an open mind and be prepared to install the type most suitable for the particular circumstances of the case. Assuming a three-phase furnace is to be installed, it is generally better to install a three-phase transformer. This becomes all the more necessary as the size is increased. I venture to say that for a large furnace taking, say, 8,000 k.v.a. or upwards the use of the single-phase shell type—and in passing it may be as well to mention that the use of the three-phase shell type is not a practical proposition for this purpose—would enormously increase the difficulties of the installation owing to induction in the leads; to such an extent, indeed, that they become impracticable also. On the other hand, where single-phase transformers are required, as in single-phase and two-phase furnaces, the circular shell type (that is, similar in section to Fig. 4, but with circular coils) has definite advantages. Put briefly it is not a case of core type or shell type. What is required is a design to suit the particular case, with as few as possible of the disadvantages which occur in the conventional types, whether core or shell, and as many as possible of the advantages of both types. For furnace work this will generally be obtained in the circular shell type with the coil faces vertical and the axis horizontal for single-phase work, and in the three-phase core type (again with the coil faces vertical) for three-phase furnaces. With reference to clamping of coil heads mentioned on page 206, amongst the disadvantages of the shell type I consider radial clamping at the corners of the coils in the rectangular-coil type to be essential, and I submit that efficient clamps can be designed which do not interfere with inspection or impede the flow of oil to such an extent as to make it advisable to omit them. In any case very little inspection of coils is possible in a rectangular shell transformer. The information gained by the inspection of the coil head is very slight, for only the top can be inspected, that is, the outer layer of each coil for less than 25 per cent of its length. This applies with equal force to the three-phase core type with rectangular coils shown on the screen. The author's survey of future requirements is very interesting. The two largest steel furnaces at present in service in this country are each of 15-ton capacity with 3,000 k.v.a. of transformers to operate them, two 1,500-k.v.a. single-phase transformers Scott-connected being used. The furnaces are identical except for the periodicity of the circuit. No tappings are used in the main transformers except the Scott tappings. The voltage variation, which is in 20-volt steps, from 100 volts to 200 volts is obtained by the use of an auto-regulating transformer. To obtain this range in the main transformers would require about 19 tappings in each. It will be readily realized from these figures that the question of voltage regulation, to which the author gives considerable attention, requires very careful consideration. Tappings in the main transformers are to be avoided wherever possible, and this cannot be over-emphasized for the reason given by the author. The three largest carbide furnaces in this country are of the three-phase type and are each equipped with a three-phase core-type transformer. As far as possible increase in size in steel furnaces is concerned, there is one solution which the author has not mentioned. This is to use two arcs in series. By this means the pressure can be raised to about 200 volts. The two 15-ton furnaces mentioned are of this type, the design of Mr. Victor Stobie. This method makes possible the use of furnaces up to approximately 60 tons with the electrodes at present available. The question of roof deterioration mentioned by the author, though somewhat wide of the question under discussion, is bound up with the question of efficient electrode economizers. It is largely due to inefficient electrode economizers, and the subsequent erosion of the roof where the electrodes enter the furnace, that the heavy reducing atmosphere possible is not maintained. This is the main cause of roof deterioration. So far as carbide furnaces are concerned,

the largest built on the Continent is of about 25,000 k.v.a., or roughly three times the capacity of the largest in use here. The author's ideal for a furnace transformer is good, although, except in extreme cases, I do not think it necessary to introduce the complication of an external reactance. Regarding the mechanical stresses possible, I would emphasize the author's concluding sentence on the subject: "That the figures given may be quadrupled." It is these quadrupled figures a designer must take into account when designing his clamps. In a rectangular coil the stresses are concentrated on the corners, whereas in a circular coil the stresses are equal all round and clamps are not required; hence my preference for the circular-coil shell-type transformers.

Mr. G. F. Sills: Furnace manufacturers in the past have been rather optimistic as to the steadiness of the current, particularly during the first period. Certainly from the electrical instruments I have watched, this would appear to be so. Owing to the large variations of current, particular attention is necessary to the design of the transformer, both electrical and mechanical. I know of a steel furnace fed by one turbo, normally of sufficient capacity for the input to the furnace, but the circuit breaker of the turbo was continually tripping and the breaker was already set at as high a figure as was advisable. By putting in an external reactance between the transformer and the turbo, the tripping of the breaker was reduced to once a month. In the paper, springs are shown at the end of the bolts supporting the main outside connections. I believe that certain core-type transformer springs are also inserted between the coils, with the idea of taking up shrinkage. The insertion of these springs, however, under the arduous conditions of furnace work where heavy surges are experienced, would probably make the springs move sufficiently to displace the coils and thus cause a breakdown, which would in all probability not have occurred had the springs been omitted. Furnace transformers are generally run at about their maximum continuous capacity, from which it follows that the temperature rise in the oil is going to be higher than in the ordinary transformer, which in a great many cases never has the full-load output taken from it. From this it follows that the usual difficulty of oil sludging, etc., is going to take place at an earlier stage than with a transformer under ordinary use. It is therefore of the utmost importance that the oil be kept in the best possible condition and the expansion vessel, which is a simple commercial device and has proved to be extremely satisfactory over a great number of years, would ensure a much greater factor of safety with furnace transformers, as, in addition to preventing the formation of sludge, the moisture is also kept from the windings. To make an oil-tight joint is a very simple matter, and adverse criticisms can be countered from practical experience, which demonstrates that this is easily carried out. During the war, a 1,000-kw. transformer of the ordinary type, without expansion vessel, was working day and night for two years on its full-load rating. At the end of two years the oil was tested and the transformer manufacturers stated that it required renewing. This, of course, is an early period for renewing the oil, but the reason was quite plain, namely, that the transformer had been run at its full-load capacity. The engineer of one of our largest cities informed me that he generally orders the ordinary transformers about 20 per cent larger than the output they will be required to give; otherwise he found that with all makes without the expansion vessel, the life of the oil was much shorter and the transformers required more frequent inspection.

Mr. R. G. Mercer also spoke (his remarks will be found on page 216 in the discussion before the Institution).

Mr. J. L. Thompson (*in reply*): Mr. Furlong seems to have taken seriously to heart the author's remarks in the paper relating to the adaptability of core and shell-type transformers to electric furnace work. No doubt Mr. Furlong is under the impression that his experience qualifies his statements, but the author begs to differ on many of the points raised. Mr. Furlong has, no doubt, overlooked the author's opening remarks in this section of the paper in order to get to points of a controversial character. While the author dealt with this matter fairly fully in the London discussion, there are one or two other items brought forward to which he must give special attention. Liability to damage in shipment is admitted by Mr. Furlong, and while many transformers are being shipped in their tanks the larger proportion are shipped separately, as Mr. Furlong well knows. Transformers have to be placed in the tanks, where owing to the small clearances at certain points, namely the neck of the tank, liability to damage is present. On site also transformers have to be, or should be, withdrawn from their tanks and inspected periodically, hence more liability to damage which with the shell type is entirely absent. Mr. Furlong's suggestion that the core type mounted horizontally will solve several of the disadvantages mentioned, may be true if a paper design is considered. There are very few large transformers constructed in this fashion, for the very obvious reason that it is a weak construction mechanically as far as the magnetic core is concerned. In the construction suggested, all the laminæ of the magnetic core are in a horizontal plane supported at each end, hence the difficulty of obtaining a rigid core can be seen if one considers the limb as a laminated beam supported at each end and free in the centre. The core tends to sag and a severe strain is put upon the insulated core bolts holding the laminæ together. This insulation in the course of time, due to vibration and sag, will fail, and will thus necessitate stripping the transformer. The coils themselves are a load on the beam, and further aggravate the cause of trouble. If, however, the sag in the core is prevented by using the coils as supports, then the coils are liable to damage, as also is the insulation between the coils and the core. Mr. Furlong has, perhaps, overlooked the above points, which in the author's opinion are not worth risking, even if the other advantages claimed by Mr. Furlong are possible. The shell-type construction is not liable to such faults, while it has the advantages mentioned in the paper. With reference to the question of jointing of heavy copper, the author's remarks refer to the connections between the low-pressure coils and their

leads, which are a necessity in the standard core-type construction. With the horizontal core type favoured by Mr. Furlong, joints are unnecessary if a heavy core section is taken, for they are similarly placed to the low-pressure coils of a shell-type transformer. Low-pressure coils, and in fact any coil, should be without joints. The low-pressure coils of all furnace transformers are wound from a through length of copper having no joints. The author has replied fully in the discussions at other Centres to the point referring to losses. With reference to the effect of the leakage flux in the two types, the author has fully explained this in the paper and would ask Mr. Furlong to consider those remarks more fully. Mr. Furlong has misinterpreted the phrase relating to the central position of tappings affecting the load balance. Early in the paper the author definitely states that adjusting tappings should be placed internal to the primary winding, and often the central position is the most convenient point. These tappings may be internal or in a central position in the winding, but yet need not be in a central position geographically. The exact position of the tappings depends on the performance required as regards reactance, and in many cases it is about one-third and two-thirds along the face of the coils. The author agrees that good design and workmanship are necessary for sound apparatus; the one is no good without the other. If constructional designs are simple, there is less liability of workmanship error, and consequently sounder apparatus can be produced. Mr. Furlong's remarks *re* Fig. 3 and the cooling surface are beyond the point, as he can see that it is only a sketch and not a design. Too many details would have only complicated the sketch and made difficult of observation the points it is intended to convey. With regard to the terminal arrangement of the high-pressure leads, this has already been fully dealt with by the author in his replies to other speakers. The half-turn transformer would have a little higher reactance due to the proximity of the iron core to the half-turn lead, but the half-turn leads can be arranged so that the fields surrounding them can be reduced to a minimum. The author is in entire agreement with Mr. Furlong *re* unscientific lay-out and the trouble and loss this has caused, and in his opinion a free and open discussion between the manufacturers of furnaces and transformers would be of mutual benefit in many instances.

Professor Walker's suggestion for reducing reactance would probably produce the desired result, but the magnitude of the task would be appreciated if one tried to cater for 50,000 amperes per phase by this means. The reactance trouble is only felt acutely when heavy low-tension currents have to be catered for, and hence such currents should be borne in mind when considering Professor Walker's suggestion. The expense and space required would, in most cases, prohibit its use. Further, on short runs of lead it would be impossible to use such a suggestion, hence other means have to be adopted. The author suggests that copper busbars 6 inches $\times$ $\frac{1}{4}$ inch in multiple and interleaved will give as good a result on the average, if not a better result, than the method under discussion. It is quite possible that the heavy quadrature current may be in part independent of the reactance of the circuit, but this cannot be a very large percentage or seriously affect the reasoning in the paper with regard to power factor. The author has many times considered the possibility of a choking effect produced by the field around the arc, but has not been able to arrive at any definite conclusion. It is possible that Professor Walker's "delayed conductance" may be similarly considered.

Mr. Frith refers to the absence of mention in the paper of switchgear, but, as the author has already stated, the paper was intended, as the title indicates, to deal with transformers. Mr. Frith's remarks concerning wave-form are not very clear; for, as he states, the wave-forms are transmitted through the transformers with very little alteration. With some transformers that are designed up to the limit, i.e. with saturated cores and saturated magnetic shunts, the E.M.F. wave becomes very peaky. With a reasonable design, however, very little change takes place. The wave-form as affected by load conditions does not affect the design of the transformers or to any extent their performance.

Mr. Ellis's remark that the paper deals with only one class of furnace is hardly correct, for early in the paper the author states that the question of accommodation of heavy currents, the insulation, and the housing and operation, are similar for all types of furnaces. The loading conditions of a steel furnace are the most exacting, hence the author is of the opinion that if a steel furnace can be satisfactorily worked, the troubles of all other types could be similarly solved. The questions raised concerning development, housing, etc., have already been fully dealt with. The adoption of a standard rating such as that suggested by the B.E.S.A. would be to the benefit of manufacturers and users in every way, and lead to more stable design. The author's definition of a "straight transformer" is one with a primary and secondary winding only, having no tappings or complicated connections. Mr. Ellis's criticism of the half-turn winding is in part correct, but it is only a mechanical problem and one which can be easily solved. To turn down a suggested improvement on account of a difficulty that can be overcome with a little thought is not progress, but suggests stagnation. An engineer should always be alert and responsive to new ideas if progress is to be maintained, and progress should be an engineer's ideal. The question of head room or overall height of a booster transformer, as shown in Fig. 6, will be a difficulty to be overcome in very large sizes. There are alternatives, however, available for the engineer in design, and for very large sizes two separate transformers would be necessary. The author did not give any plans of furnace lay-out, for the reason that each plant requires special attention due to location of furnace and transformers and the surrounding gear. Also, some firms are rather narrow in their views and might treat such diagrams as a breach of confidence. The author, while deprecating this point of view, has nevertheless to consider it.

Mr. Ratcliff seems to fear the heavy currents consequent on switching in large transformers. The

magnitude of these currents depends on the design and switching arrangements, and in most cases it rarely exceeds 50 per cent of the normal load current, and then only for one or two periods. The sudden and heavy overloads referred to by the author are those experienced during the melting period. If a 2,000 k.v.a. plant requires peak loads due to short-circuits in the melting period of 1·6 to 2·3 times full load, then the supply companies have to cater for these loads. On a small station of, say, 10,000 k.v.a. this peak represents a large percentage and hence must be considered. The author does not know of any failure that could be attributed to "switching in." All failures, as far as his experience goes, can be traced to load periods, through failure of insulation, tappings, switchgear or improper operation, and chiefly the latter cause. Charging resistances are not all that Mr. Radcliffe suggests, and the author knows of many plants in which they have had to be cut out so as to give satisfactory operation. The E.M.F. wave-form is hardly affected by the transformer unless, as the author has already stated, the design be a narrow one and high saturation be used in the magnetic core or magnetic shunts, if any. Any abnormal wave-form incidental to load conditions will be found also on the supply side of the feeder.

Mr. Binns is entirely in agreement with the author on many points and especially the causes of the trouble experienced in the past by all manufacturers of furnace transformers. The serious overloading has in many instances been the sole cause of the short life of the transformer. As these conditions are somewhat excusable at a time of national crisis, such as during the war, the author hopes that steel manufacturers and other users of electric furnaces will be more moderate in their demands and adhere to the designed ratings. The increase in section from 2 or 3 inches below oil level to above oil level is in the author's opinion highly desirable, for in many cases the overheating of the leads has resulted in higher transformer temperatures. This is because the heat there generated has flowed into that particular part of the circuit on account of a difference of temperature. High temperatures in the leads tend to disintegrate the oil at the oil level, and hence should be avoided. While the author states certain minimum distances between transformers, he does not object to higher values. The distances given are the minimum for efficient ventilation. Mr. Binns's remarks about core and shell-type design are anything but clear, and the author would suggest that Mr. Binns is, from his remarks, hardly familiar with the true definition of core and shell-type transformers. Mr. Binns suggests that these problems should be approached with an open mind, and the author agrees, for an open mind is one of the most valuable assets of an engineer. The question of horizontal cores has already been dealt with by the author in his reply to Mr. Furlong's remarks. Mr. Binns's remarks concerning mechanical stresses on rectangular coils are in the author's opinion erroneous, and he would refer Mr. Binns to his reply to Mr. Holbrook (page 222).

The author is also familiar with a furnace plant similar to that cited by Mr. Sills. The machine supplying the furnace was unable to cater for the peak loads during the melting period, because the voltage fell away in addition to the breaker tripping. The introduction of external reactances of such a value as to limit the peak to a permissible maximum overload of machine, brought about the possibility of a continuous run. The use of springs internal to the windings is hardly a question for this discussion, but if Mr. Sills refers to the paper on "Large Power Transformers," by Mr. A. G. Ellis and the author,* he will find the question fully dealt with. The question of oil sludging has been fully dealt with in reply to various speakers at other discussions, so there is no need to amplify it here.

Mr. Hill is quite correct, in the author's opinion, in stating that an installation of the type under discussion is often spoiled by the cheese-paring policy of many furnace builders in connection with the cost of the electrical plant. The author entirely agrees with Mr. Hill in his suggestion of the use of intermediate transformers when a supply has to be taken from an extra-high-tension system, such as one for 50,000 volts and upwards. The above case would be a rare occurrence, however, for on an extra-high-tension system an intermediate pressure of 5,000 to 6,000 is usually available for local distribution. Figures of rating, overload and temperature are often not consistent in many specifications, and if the customer would give his maximum rating and maximum temperature requirements, he would in many cases get a better and possibly a cheaper transformer. Mr. Hill's remarks on this point illustrate this fact. The curves in Fig. 9 are plotted against nominal kilovolt-amperes, which figures are clear to a layman, whereas equivalent kilovolt-amperes would be unintelligible to the lay mind, though clear to a designing engineer. The latter can, however, easily plot equivalent kilovolt-amperes by multiplying the abscissæ by the ratio 1·31/1 for full output and 1·155/1 for constant-current transformers. Mr. Hill has correctly surmised the reason for a ratio of 1·31/1 in voltage. With reference to the cost of furnace transformers, Mr. Hill must not overlook the fact that during the period between the reading of the above mentioned paper on "Large Power Transformers" and the present paper, several Government wages awards were granted to workmen, which necessarily had to be covered by an increase in cost. Allowing for these awards, a furnace transformer is approximately 10 to 15 per cent more expensive per equivalent kilovolt-ampere, or per lb., than a standard power transformer.

* *Journal I.E.E.*, 1919, vol. 57, p. 547.

DISCUSSION ON

"THE PROTECTION OF ALTERNATING-CURRENT SYSTEMS WITHOUT THE USE OF SPECIAL CONDUCTORS." *

North-Eastern Centre, at Newcastle, 8 March, 1920.

Mr. G. L. Porter: I wish at the outset to congratulate the author upon the reverse relay described in the paper and especially upon the voltage characteristic shown in Fig. 12. He has succeeded in retrieving the reverse relay practically from the scrap heap and in making it suitable for a great many positions where ordinary overload relays do not meet the requirements, and where, owing to the absence of auxiliary conductors, etc., the cost of balanced protective gear would be prohibitive. The author, in his opening remarks at this Centre, stated that the paper was not intended to apply to an extensive power scheme, but only to the more usual small undertaking; but as no such statement appears in the paper itself, and as small schemes have been known to become large—either through growth or linking up—we must consider the subject in the light of the large scheme. There are two reasons for the adoption of protective gear. These in themselves are quite distinct, although an attempt to meet the one set of requirements may to a certain extent meet the other. These are: (*a*) to minimize damage to faulty apparatus, together with the prevention of damage to other apparatus through which the fault is fed; (*b*) maintenance of continuity of general supply, by removing any fault which is tending to interfere with such supply. Any protective gear which is installed purely to meet the requirements of (*a*) may be considered to be an insurance premium on the value of the apparatus protected, and the position is not affected by the amount of other plant connected. In the case of gear installed to comply with (*b*), any increase in the size of the system will increase the value of the general supply, and should the system be doubled we should be prepared to pay twice as much on the protective gear installed to look after any individual piece of apparatus. The importance of (*b*) will depend on the value placed by the management on continuity of supply, but gear installed to meet (*b*) will usually also meet the requirements of (*a*), whereas the converse is not true. Far too much importance is often attributed to low current-settings, and too little to excessive time-lags. It is true that any current above the continuous rating of the apparatus will damage it in a certain length of time, but in practice the faults which do occur (except in the case of comparatively low-voltage overhead lines with insufficiently earthed brackets, etc.) are such as to be well above the settings of even the least sensitive forms of balanced protective gear. And it is such faults which, having to draw their supply from the kinetic energy stored in the rotating plant, are most likely to interfere with continuity of supply unless cleared in the minimum time. As the author does not mention damage to plant, and classes continuity of supply along with considerations like simplicity, it is obvious that he has assumed (*a*) to be the real reason for installing the gear. He states on page 391 that the majority of faults start as earth faults, and yet on page 393 he makes the extraordinary claim for time-lags that they will result in preventing the switch from opening until the current has died down considerably. This claim is obviously made on the assumption that the fault starts as a short-circuit. Actually the time-lag is giving the fault an opportunity to become a short-circuit before the switch opens, and may result in the latter opening on the very peak of the curve. Although there is considerable scope for reverse relays in certain cases, I would point out that in general such relays only give a first approximation to the location of the faulty apparatus, and the author has to fall back on the method of graded time-lags. Even in the most complicated system shown (Fig. 16) there are only four substations and yet there are minimum time-lags of $2\frac{1}{2}$ seconds. One dare not try to imagine those necessary on a system like that in this district where there are about 400 substations. Our experience in this district is that when a fault occurs on a line protected by balanced protective gear with quick-break switches, it is unusual for the staff in the power stations to be aware that anything has happened, whereas even a much shorter time-lag than those mentioned by the author results in more or less disturbance on the system. The ordinary inverse time-limit relay has too short a useful range, and due to various imperfections largely resulting from the use of iron in relay or transformer there is the horizontal part of the curve commended by the author. These excessive minimum times could be avoided were higher current-settings used. Should the necessary current-setting come out too high, an additional relay with lower times might be used to extend the current range downwards, until such time as the author or some other inventor brings out a relay with an effective range long enough for the purpose. The time-limit fuse has a longer effective range than the relay and has, what is an important feature in many cases, viz. low inductance. In really modern switchboards, current-transformer primary shunts (Fig. 27) cannot be used, and when a fault occurs close to a station where there are many lead-covered cables connected to the board and where there is consequently large electrostatic capacity with minimum inductance, at the instant of breakdown when the capacity is suddenly being discharged the rate of change of current in the current transformer primary reaches an enormous value and the secondary voltage with an inductive circuit is correspondingly large. I have known it jump across $1\frac{1}{2}$ inches in air between an ammeter terminal and the case. Although this voltage is only transient, there

* Paper by Major K. Edgcumbe (see page 391).

is considerable risk of breakdown between the turns of any relay winding not shunted by a fuse. On page 391 the author refers to "Simplicity of the apparatus involved," but it seems to me that three aspects of simplicity are involved: simplicity of main circuit, simplicity of system operation, simplicity of secondary circuits. I have stated these in the order of relative importance, and would suggest that the first has not been given due consideration in the design of certain forms of protective gear. Merz-Price feeder protection which uses straight-through bar-type-primary current transformers entails the minimum complication of the main circuit and, along with the other forms of really discriminating protective gear, interferes to the minimum extent with system operation. Reverse relays such as the author's necessitate potential transformers and, however robust these may be in themselves, their connecting up and their protection are weak spots on any switchgear. In addition, no scheme of graded time-limits can fit in with the various arrangements of network resulting from the opening and closing of switches on an interconnected system; and to ask supply engineers to run their systems to suit the form of protection used, or to reset all their relays when any switching is carried out, is asking a great deal too much. I am also afraid that such engineers would not appreciate the author's suggestion of no-volt relays arranged to trip feeder switches in substations especially in cases where there is no continuous attendance. There seems to be an impression that Merz-Price protection involves excessively high settings. Although this is a mistaken idea, recent improvements have considerably lowered the settings available. These consist of the Beard screened pilot cable and the Fawsett-Parry sensitive relay. So far I have dealt mainly with line protection, but in the case of transformers faults between turns nearly always result in the bursting of the winding and sufficient resulting fault current to trip any gear. In generators, however, the winding is usually much more robust, and gear which will operate at once on a fault between turns would be very valuable. The only gear that I have heard of which seems likely to do this is that put forward recently by Kayser, in which the voltages of the two halves of a generator winding are balanced against each other. In connection with the author's claim that the self-resetting feature of his relay is an advantage, I would state that we have found it advisable to insist that an indication be given of which phase relay has operated, and the most satisfactory way of ensuring that the indicator has been reset before the switch is again closed is to use the relay movement as the indicator. In the early part of the paper the author recommends earthing the neutral of a system, and yet on page 405 he gives in tabular form comparative figures of the current which must be passed by the neutral resistance in order to trip various kinds of relays. The underlying assumption apparently is that the smaller this current the better. But the smaller the current passed by the resistance the more the system departs from the ideal of an earthed neutral, and on the large power scheme in this district the value of the resistance is not based upon relay settings at all, but on a compromise between two opposing aims. We wish to limit the earth fault current in order to prevent the induced voltage in adjacent telephone cables from causing damage. At the same time we wish to anchor the neutral to earth potential sufficiently to prevent one fault resulting in the breakdown of weak points on other phases and so producing simultaneous earth faults, when the current will be no longer limited by the neutral resistance and much more damage result. This latter consideration necessitates a much lower value of neutral resistance than would be chosen from the relay-tripping point of view.

Mr. H. W. Clothier: In the author's verbal remarks he mentioned that the devices described in the paper were intended for existing systems where a limited purse did not warrant the use of the more perfect balanced protective systems of the kind which had their origin and development on the large power system of this district. This is an important admission, and it should be observed that a different impression might be created on reading the paper. I find there is but little in the paper which can be utilized to advantage on large systems, and I now understand that it is not the author's intention to disturb the well-established practices. The instantaneous isolation of faults on large power-supply systems with extensive interconnected networks has had considerable attention in this country, and has been found by experience to be a very necessary adjunct to the problem of continuity of supply. At first glance of the paper I was led to hope that the author had found some useful application of Price's leakage protection. Leakage protection in its early days was considered for generators, busbars and feeders, but its use settled down to mines, where it was essential to isolate faults to earth with great rapidity in order to prevent such faults from causing "open-sparking." The special virtue of leakage protection is its property of operating instantaneously at light fault-settings, clearing such faults so promptly as to prevent them from spreading to more serious disturbances. I am disappointed, therefore, to find that the author's proposals are all based upon a delayed action, thus depriving leakage protection of its main virtue. The simplification of relays and protective systems on large power systems has been one of the fundamental principles. A good margin for reliability of operation is of greater importance than extreme sensitiveness in operation, and I would prefer a system which allows for the use of robust mechanism and relays to one which requires extremely sensitive devices, so delicate in construction as to need sealing up like a switchboard instrument. Notwithstanding the author's opening remarks about "simple means and well-tried apparatus," I find that the relays proposed are really of a complicated nature, involving connections which are so complex that they have to be omitted from the diagrams. Time-lag discrimination prolongs the life of the fault and thus increases risks of fire and in other ways spreads the damage. In many cases the fire may lead to serious explosions. It is important to limit the damage caused by a fault, particularly on generators where a speedy clearance of the fault may reduce the cost of repairs by some hundreds of pounds. Further,

time-lags upset continuity in the running of synchronous plant. The author estimates an interval of 2 seconds as the upper limit, and for substations containing synchronous machinery this figure must be considerably reduced. It would be helpful to have a recognized limit. Possibly the interval will vary with the experiences on different systems according to the size and type of plant. On inquiry made of a very large system, I was informed that 0·5 second is an absolute limit. In this case protective apparatus should not occupy, in its complete cycle of operations from the occurrence of a fault to the opening of the switch, a greater time than 0·25 second, as there must always be a good margin in design to allow for the unexpected to happen. The time taken by the mechanism of switches when operating from the passing of current through the trip coils to the separation of the sparking contacts, may be 0·1 to 0·15 second, thus leaving only 0·1 to 0·15 second as a maximum for the operation of relays. Graded time-lag discrimination is out of the question in these circumstances. Another case against time-lag as a discriminating protection on feeders and generators is associated with Fig. 5, which shows the transient short-circuit characteristic of a turbo-alternator. This would represent a fault in the nature of a dead short-circuit suddenly applied, and the current would die down to a lower value before the switch opens, with the advantage of reducing the stresses of the switch. But if the fault at its early stages is an incipient one, such for instance as an earth fault limited in amplitude for a time by the earthing resistance, the fault grows during the allowed time-lag. In that case the time-lag acts to the disadvantage of the switch. The fault may even develop to a short-circuit between phases at a moment which would concur with the separation of the sparking contacts of the switch, in which case the switch, in consequence of the time-lag, would have to break circuit at the extreme maximum current wave. This would be disastrous to a switch designed to take advantage of the use of a time-lag. Referring to Figs. 15 and 16, the author states in one place that "reverse relays" cannot be used since the flow of current may be in either direction under quite normal conditions, but in another the relays R2, R3, and R5, are called "reverse relays." I understand the explanation of this contradiction is that the relays used are not strictly reverse relays, but rather overload relays with a potential element so arranged that operation is on overload in one direction only. Is it not a uni-directional overload inverse time-limit relay? The device is dependent upon a potential element which necessitates the use of a potential transformer, particularly undesirable when used upon high-tension substation gear. At best, potential transformers are a weak link in the design between high and low tension. Moreover, when the system becomes larger and more complex, the greatest difficulties will be encountered in finding places where these uni-directional devices will work, owing to the fact that the direction of power is constantly changing under normal operations, and any additional substations or generating stations will call for a revision of the settings of relays throughout the system. Another misleading comparison occurs under "protection of parallel feeders" (page 397), where it is stated that the use of parallel feeders connected to the busbars through transformers, enabling the transformer to be isolated, as well as the feeder, eliminates the risk of isolation through an abnormal rush of magnetizing current, such as may occur with Merz-Price transformer protection, for example. Now the author has made the claim for the differential reverse parallel feeder protection, that it requires no discriminating time-settings, thus following the fundamental principles of the Merz-Price or split-conductor protection. He does not state his settings, but the protective gear does not prevent the magnetizing current on switching in power transformers, and this current is just as likely to trip out parallel feeder and transformer protection by reason of the current-rush occurring on one feeder when switching in with one side of the transformer open. With all systems of parallel feeder protection one is confronted with two conflicting features:—(1) That a comparatively fine setting of the relays is required for the purpose of discrimination because the fault current passes through both the sound and the faulty cable; (2) whereas a heavy setting is required to eliminate the effects of out-of-balance which always occurs, even in the best made transformers. It would be interesting to have from the author particulars of the setting of relays, and the experience obtained from the working of them in those cases where they have been "well tried." But if the setting is anything less than double the full-load current of the feeder, I would expect to find the magnetizing current difficulty in switching in a parallel feeder and transformer. One of the troubles with parallel feeder protection is the "open circuit," whether it be in the nature of a fault or the operation of a switch. The opening of a switch at one end of a line creates an out-of-balance between the pair at the other end of the line, and the chances are that the feeder carrying the load is the most likely one to be tripped out.

With regard to parallel feeder protection, the work of the late Captain Waters deserves mention. I am glad to see that the author claims the absence of a discriminating time-setting and I note that the problem becomes a simple one. I agree to the instantaneous operation of the system of parallel feeder protection, but it is difficult to ensure that the relays which operate on a balance of current and discriminate for direction thereby always operate correctly. It does not always follow that the faulty side carries the greater current. The operation of any one switch in a group of four disorganizes the protection remaining. No system is really complete, nor can it be simple, if thought has to be taken of the effect of one operation upon another. The whole must be made up of units of protection capable of independent operation without interference with neighbouring units. I am glad to note also that at the conclusion of the parallel feeder section of the paper there is a reference to substations fed by a pair of feeders treated as a single unit. In these cases the system is much simplified by the use of plain relays; it is independent of potential element and time-limit. This, in fact, is known as split-conductor protection (Wedmore and Hunter patents) applied to parallel

feeders, and it simplifies not only the relays but also the switchgear, as one split-conductor switch panel only is required at each end of the pair of feeders. This is one happy exception to the use of time-limit and reverse relays which the author has made in his recommendations. This method has been usefully applied on large systems, has many advantages, and is a handy way of re-organizing the protection on an existing system. On page 394 the author refers to Merz-Price and split-conductor protection, and adversely criticizes these, as he says the instantaneous action is " entirely lost " on the occurrence of substation busbar faults. This is misleading. The principles of Merz-Price protection may, if required, be applied to the isolation of busbar faults, but even so it is desirable at the main outlet for transmission, such as feeders leading out from the power station, to have a second line of defence, which I would prefer to be in the form of a short and definite time-limit overload release with a reasonably heavy setting. The author has this second line of defence on his graded overload system, but it labours under the disadvantage of needing a long time-lag. It should be noted that the adverse remarks are made under the heading of independent feeders for which, in the ordinary course, the point of using Merz-Price and split-conductor is not so vital as for ring mains. From a continuity of supply point of view, a lay-out on the lines of Fig. 4 would be considered very bad and would not be a practical proposition upon a large supply system. I think that low-voltage devices should always be accompanied with a time-limit action to guard against incorrect operation during momentary voltage irregularities, but I do not think the author's suggestion (page 400) to introduce low-voltage devices for the purpose of clearing busbar faults in substations will meet with general acceptance owing to the danger of a fault on one part of the system reducing the voltage elsewhere, which might operate such relays in several substations and thus constitute a menace to the continuity of supply. The introduction of a bias control of protection system is one worthy of full consideration, and in this connection a reference to McColl's patents should be made as well as to Fig. 10.

One salient factor in the general principle of earthing the neutral is to fix the neutral point at earth potential as a precaution against surges and high-voltage phenomena. For this purpose the ohmic resistance should be as low as possible and, were it not required to reduce the shock to the system on the occurrence of earth faults, the neutral point might to advantage be connected solidly to earth. In determining, therefore, the current which should be allowed to pass through the earthing resistance, the current required for the operation of the relays should not be the only consideration, and so the table on page 405 comparing the minimum current in earthing resistances loses some of its significance. When instantaneously operated relays are used, there is no particular virtue other than a possible reduction in the initial cost of the resistance in using earthing resistances of high ohmic value, and neither the cost nor the type of the resistance should be the only determining factors in the selection of fault-isolating devices. The amount of the resistance cannot be determined only as a percentage of the current of the largest generator, for it must also take into account the current required to operate protective apparatus on the feeders most remote from the generating station. To rely upon the negative temperature coefficient of the artificial neutral resistance as a current-growing medium is contrary to the principle of instantaneous isolation of faults and I think, therefore, the comparison which might be drawn from this table between Merz-Price or Merz-Beard protection and reverse relay generator protection does not count for much. Anyhow it is quite possible to reduce materially the current-setting of the Merz-Price or Merz-Beard (self-balance protection), if all that is required is a finer setting. As a general rule I think it is better to have the coarser setting. Relays are all the better for plenty of margin for operating inaccuracies. Merz-Price and Self-balance (Beard) generator protection are in satisfactory operation at or below percentage fault-settings comparable with that given for the reverse relay, viz. 35 per cent of generator capacity. But I would rather increase the minimum current through the earthing resistances. I believe the use of reactances for earthing the neutral is not without practical precedent. The theoretical objections taken by the author may be correct in substance, though in effect somewhat overdrawn. There is at least this to be said in favour of the reactance, that it is a more mechanical piece of apparatus and for an equivalent current-rating it may be made more compact. It also has the advantage that in construction it lends itself to the principle of complete metal-clad enclosure of all conductors. The carbon powder resistance shown (Fig. 22), consisting of a standard size of earthenware troughing built up in the required number to suit the voltage of the system and the current to be passed, may be a reasonable form of open-type apparatus and quite suitable for small currents, but for larger currents and higher voltages the troughs are proportionately more numerous. In consequence the initial cost and space occupied advance beyond what might be expected of a construction if designed expressly for the larger currents. Except for the purpose of saving in initial cost, the current-growing characteristics of carbon are not necessarily advantageous when used as an earthing resistance. Considered from the point of view of the protective systems, for example, it is contrary to the demand for instantaneous release of faults. In this light it would be highly undesirable to use a resistance as stated in the paper (page 404), which would require 15 to 20 seconds to allow the fault current to develop to the amount required to operate the switches. It was opportune that Mr. Porter was called upon to open this discussion. His view is that of the user. The balanced protective systems which the author has mentioned in the paper with scant praise are the outcome of urgent necessity which had at all costs to be complied with. It is fundamental to the design of relays used for the systems advocated by the author to include a current and potential coil, whereas, with the balanced systems of Merz-Price and split-conductor, the simplest form of relay is used, namely, one having only a current coil. This is an important distinction in principle, as it carries with

it the use or not of potential transformers and connections. The author asked for comments from switchgear manufacturers on his statement that the objection of the past to the use of potential transformers has been due to the construction and arrangement of them upon the switchgear. In order to overcome this he proposes to use single-phase transformers with the phases well separated and the neutral earthed. In some switchgear single-phase potential transformers in separate chambers are used, but I do not think that is a solution of the objection to using potential transformers for protection in substations. There is no insurmountable difficulty in separating the phases, but potential transformers are subject to phenomena of their own, such as abnormal magnetizing current and abnormal voltage in end turns at switching operations and changes in the main voltage. The potential transformer may be made very substantial, but at best it must be the part of the switchgear where the high-tension conductors are carried close to low-tension conductors and earth. Separating the phases does not cure this. Good insulation between turns, particularly the high-tension end turns, the immersion of all conductors to avoid sparking-over at terminals, is the best safeguard; but given all this, it is not desirable to place potential transformers directly on the busbar. There should be an oil-break switch between them and the busbar. It is not customary to earth the neutral point of potential transformers for wattmeters. Presumably on insulated neutral systems it would not do because, in the event of one phase on the main network going to earth, the full voltage would come across the potential coil on the other phases and would considerably overload them. On an earthed system it is not permitted to earth at more than one place, so that to earth at the neutral point of potential transformers in substations would be a technical, though perhaps not serious, breach of the Board of Trade rules. I agree with the author that it is not permissible to mix the protective gear and wattmeter current transformers owing to the complication of connections involved, and the risk of the meter man accidentally interrupting the protective gear connections, and maybe thereby tripping out switches carrying load. The same argument applies to potential transformers when required for protective gear. If these ideals are carried out, the multiplicity of potential transformers in substations would constitute an extravagance in maintenance costs. The risks to the potential transformer coils and connections are repeated on the potential coil and connections of the relay. Unless very substantially constructed, any pressure coil is subject to greater risk of deterioration than current coils. It is much better to cultivate the use of protective systems which do not require the service of such parasitical details as potential transformers and potential coils on relays.

Mr. J. R. Beard: The author rather disarms criticism by prefacing and concluding his abstract of the paper with statements that it is primarily intended to apply to the protection of existing systems of relatively small size, and should therefore not be construed as a criticism of the well-known protective devices using "special conductors" for extensions on large systems. It is a pity that the author's views were not more clearly expressed in the paper, as both the title and the contents would, without such an explanation, lead the reader to think that the methods described were a universal panacea for all system-protection difficulties, at the negligible expense of a few special relays. The inference from the author's introductory paragraph is that feeder protection is a pressing problem which still awaits solution. The actual position to-day is that apart from relatively minor improvements, the problem is solved for new feeders. I see no reason for requiring a general solution applicable to both existing and new feeders, especially since, so far as linking of systems is concerned, this will usually be carried out through the medium of new feeders. It is always a mistake to allow past practice to influence future practice unduly, more particularly in a growing business such as electricity supply, in which at the present rate of progress systems double in size at least every 10 years. In so far as the paper assists us in dealing with the admitted difficulty of the protection of existing networks it is to be heartily welcomed, but it is only fair to point out that in the case of at least one very extensive existing network a practically complete scheme of protection using paired cables for split-conductor protection is in successful operation. I believe the author will agree on reflection that his criticism on page 394 of the Merz-Price and split-conductor systems is not quite fair. I do not see any disadvantage in the "watertight compartment" feature. In fact, it appears to me to be an advantage, as the feeder is then protected for good and all and is not mixed up with the rest of the system, so that it is unaffected by extensions. In any case, the very rare occasions when busbar faults occur can be taken care of by methods akin to those which the author recommends for general use. Thus, it appears to me, that so far from these special systems leaving no second line of defence, the author's methods really abolish the first line of defence and rely on the second. It is quite a mis-statement to say that in using overload protection for the second line of defence the simplicity and instantaneous action of the automatic protective gear is entirely lost. It is only lost in the exceedingly small number of cases where a busbar fault occurs. I would, however, point out that in the parallel feeder arrangements mentioned later on page 400, the same disadvantage is admitted and a rather extraordinary remedy proposed, namely, low-voltage relays on all feeders into the substation—a system which I think operating engineers would agree would not be practicable. From time to time I have found engineers fight shy of the Merz-Price and split-conductor systems because of the skilled supervision which they are believed to involve. I hesitate to think of the supervision which would be necessary with the author's systems where, as mentioned on page 395, re-adjustments of time and current settings are continually necessary. I agree that there is a limited field for parallel feeder protection. In general, however, it is not economical to run two feeders by the same route, and hence any protective system involving parallel feeders is of very restricted application.

The saving on the main cables by adopting pilots or split-conductors much more than offsets their additional cost compared with parallel feeders. As an instance, I may say that in connection with my paper * on the "Design of High-Pressure Distribution Systems" I worked out, as a matter of interest, a theoretical comparison between a Merz-Price protected network and a parallel feeder network and found the overall cost of the latter to be at least 20 per cent greater. In the section dealing with the protection of interconnectors and ring mains I believe the author endeavours to apply, to conditions which are beyond their capacity, the admittedly useful relays which he has described. In Fig. 16 he shows an arrangement for two power stations and four substations, and already admits the time settings are long, and recommends the doubtful complication of automatic reduction of settings with fall of pressure. I would ask him whether he would propose to extend these methods to, say, two power stations and 50 substations on an interconnected system, much less to the 16 power stations and nearly 500 substations on the large network of the North-Eastern Power Companies. The author himself admits that the ring main presents a difficult problem. I would, however, point out that it is primarily for the ring main that the Merz-Price and split-conductor methods have been developed. In certain instances there is room for the use of the forms of leakage protection shown in Figs. 2 and 3. It is regularly used on large systems in this district for single tail-end feeders. I may mention as showing that this limited field was appreciated by Mr. Bernard Price, one of the originators of the Merz-Price system, that he had the original patent for the scheme shown in Fig. 3. Turning now to the protection of generators, there are three points I should like to mention. First, on page 405 the author has referred to what he calls the Merz-Beard, or what is more generally known as the self-balancing system of generator protection, and gives the current setting at 50 per cent of the generator capacity for both this system and the Merz-Price. I believe that no figures of the settings used on the self-balancing system have hitherto been published, so that I do not wish to criticize the author but trust he will not mind my correcting him. Several large machines up to 15,000 k.v.a. are running protected by the self-balancing system with settings of about 10 per cent, and it has been proved under continued operation that such settings are perfectly stable with this system. Secondly, on page 401, reference is made to the use of reverse power relays for generator protection, with the object of protecting against loss of field, internal faults between turns, or seizing of bearings, I am very doubtful whether such relays would really function under these circumstances, at any rate as reverse power relays, since there is no reason why power should flow into a loaded machine from the busbars, except in the exceedingly unlikely case of the energy loss in the fault on the machine exceeding the load on it. In this connection it should be borne in mind that even if the field is open, the turbine governor is not affected and the same kilowatts are still generated, although at a very low power factor. Thirdly, I should like to mention the rather promising system of generator protection due to Mr. Kayser for combining protection for faults between turns with protection for faults to earth and between phases. Although this system has not been tried out commercially, it probably will be at an early date, and may prove a very convenient method of dealing with the difficult problem of preventing faults between turns developing into faults to earth and thereby burning the alternator core. The principle of this "mid-point" protective gear is to take a tapping at some intermediate point on each phase winding of the generator, preferably the middle, and to compare this with an equi-potential point on a small reactive winding in parallel with the phase winding. The relays are designed to disconnect the alternator when there is any voltage difference between these two equi-potential points. Such difference can of course only occur in the event of turns on either the alternator or reactance winding being short-circuited, due to a fault.

* *Journal I.E.E.*, 1916, vol. 54, p. 125.

Mr A. Collins: The author has to some extent disarmed criticism by explaining in his introductory remarks that his proposals are intended as applicable more particularly to small systems, where apparently the special apparatus used in the balanced systems of protection is not considered to be a commercial proposition. The objections to such apparatus, however, are not so serious as might appear at first sight, as extensions and linking up frequently lead to the rearrangement of existing switchgear, on the score both of distribution and of breaking capacity, and this affords opportunities for the installation of new apparatus, while there can be no objection to introducing improved systems on extensions. While I am prepared to admit that the special apparatus of the Merz-Price and split-conductor systems renders it impossible to describe them as general solutions, I cannot agree, as the author would appear to infer, in the introductory paragraph of his paper, that the proposals he makes are more general, as everything depends upon the question of time limit. In addition to delaying the action of the protective devices, in order to secure discrimination, the time limit has to be increased at points nearer to the power station, where short-circuits are of necessity of greater intensity. The balanced systems of protection are designed for instantaneous isolation of faulty sections, and while the author deals with the effect of a fault, particularly on rotating machinery, and suggests the desirability of quick operation, he proposes to carry out most of his protection by means of a time-limit system. It is his intention, I think, that a fault should be disconnected as quickly as possible, within the limitations of his proposals. Speed of operation is one of the most important features of a protective system, as this has particular reference to the behaviour of rotating machinery when a fault occurs on the system. The author refers on page 393 to the time limit permissible, and considers that for synchronous machinery the maximum figure of 2 seconds suggested must be considerably reduced. It is of interest to consider the case of ordinary induction motors, which form an important part of the load in industrial areas. An

average induction motor falls out of step at about 60 to 70 per cent of its normal working voltage, and if it is to continue to run at a voltage below this and still carry its load, with the possibility of sudden overloads, it is merely by virtue of its kinetic energy and the condition is an unstable one. Data is lacking and it would be of interest to have the opinion of designers as well as of operating engineers on this point. I have in mind that the time which an average induction motor would run with the voltage reduced appreciably below the "pull-out" voltage is a matter of a few cycles. In Fig. 16 it is of interest to consider what would happen if a fault occurred on the feeder running from G S_2 to S S_4 where a time limit of 2½ seconds is suggested at the power station end, bearing in mind that this diagram represents a very small system. Assuming an earth fault, the current being limited by an earthing resistance, as it is impossible to isolate this fault for at least 2½ seconds, it is quite possible that sufficient heat would be generated to cause it to develop into a fault between phases, giving a short-circuit to which there would be no limit other than the reactance of the plant. It is possible (and although this has been mentioned before, I should like to emphasize it, as it is important) that this short-circuit might develop just at the time when the feeder switch-contacts were separating, so that the switch would have to interrupt the maximum value of the short-circuit transient. If advantage had been taken of the suggestions contained in the paper as to the beneficial effects of time-lag, and in determining the requisite rating of the switches account had been taken of the reduction of breaking capacity that might be possible due to delayed action, then the results would probably be disastrous. If, however, the short-circuit occurred earlier, at the end of 1 to 1½ seconds for example, the heavy short-circuit would be left on the system for anything from 1 to 1½ seconds, pulling down the voltage and throwing out of step all the machinery running at the time.

Dr. E. Bowden : There is one matter in the paper which, although bearing only indirectly on the main subject, is I think of sufficient interest to warrant comment, viz. the author's statement that the use of reactance for earthing the neutral of a system cannot be regarded as a practical proposition. While preserving an open mind on the subject and recognizing the disadvantages of a reactance, one cannot but feel that the author has dismissed it somewhat summarily. In particular, I would refer to the work recently published by Professor W. Petersen in the *Elektrotechnische Zeitschrift* on the limitation of the earth current by means of an earthing coil. The earthing coil is so dimensioned that, under the phase voltage, it takes a current of the same magnitude as the capacity earth current. Thus, apparently, it is sought to set up in the system precisely those conditions which are usually regarded as extremely dangerous. The conclusions arrived at from theoretical considerations are supported by experiments on an extensive network, while the experience obtained in practice with such a reactance on a large system is so remarkable as to justify further consideration of the scheme.

Mr. H. M. Theaker (*communicated*) : There are many problems to be solved in installing protection gear for isolating faulty apparatus from a system. One of these is that only the faulty section is cut out, and as soon as possible before the disturbance to the system by the fault can upset the running of synchronous machinery. The author obtains discriminating action by grading the relays with different time-lags. I think this method would be only successful on the very smallest of systems, as the setting of time-lags become complicated on a large one ; even then the time-lags mentioned seem to be much too long where synchronous machinery is installed. A system of balanced protection seems to meet the case much better, which would have to be installed some time later in any case, when the system must eventually grow to be a much larger one. With reference to generator protection, a method of using a balanced system of protection for cutting out a faulty machine does not seem to be enough in itself, and a reverse-power relay is necessary so that the generators will be disconnected from the busbars in case of mechanical trouble of the machine. Sometimes, however, three relays are fitted, one in each phase, consisting of merely single-phase wattmeter elements with the moving part prevented from rotating by a stop, but on reversal closing a contact in the tripping circuit of the oil switch. If these relays are connected with the pressure element in delta and the current in star, which is often done, the generator will be disconnected when the power factor falls below 0·5, and this is not always desirable. Another method would be to use one relay connected up three-phase like a three-phase two-element wattmeter, then the generator would not be disconnected at all while any power was being generated in the forward direction whatever the power factor. With regard to the methods of tripping the circuit breakers, a battery seems to be the most reliable and simple means of supplying the energy. Primary batteries of the Leclanché type will meet the case quite well, requiring, as they do, little attention. Accumulators used for this purpose would, however, require a good deal of attention, as they would never get discharged except when done periodically in order to keep them in a healthy condition. The battery may at this time be called upon to do its duty in tripping a switch when it is already in a discharged condition, resulting in failure. An accumulator used for this purpose where there is not much work to do would probably not have a very long life. With regard to Fig. 25 where the current from the current transformers is used to trip the switch in case of overload, I am of opinion that a fuse connected across the trip coil is quite satisfactory and simple, although the author does not seem to like using fuses in this capacity as he mentions on page 393. There is, however, room for a lot of improvement in the design of suitable fuse holders.

[The author's reply to this discussion will be found on page 636.]

SCOTTISH CENTRE, AT EDINBURGH, 9 MARCH, 1920.

Mr. C. W. Marshall : The author points out the advisability of not breaking circuits at the time of maximum current, but I think it better to stake everything in an attempt to clear faults before they develop between phases. The most obvious way of doing this is by increasing the speed and sensitiveness of the relays and switches. This is especially desirable in systems which include synchronous converting machinery. I do not share the author's regard for the induction relay as I have found it to be subject to the trouble of all instruments using jewels and pivots and, in addition, the time calibration is liable to alter due to the demagnetizing action of the alternating field produced under short-circuit conditions. The example chosen on page 397 to illustrate the author's view that biasing is valueless does not represent practical conditions. An out-of-balance of 5 per cent could never be tolerated, and it is generally quite easy to balance within 0·5 per cent. Biasing to this extent is quite satisfactory. The biasing problem is closely analogous to that of compensating induction watt-hour meters. In these instruments, if the design is sound, a fair degree of accuracy can be obtained without the use of compensating devices, and using these the accuracy can be very high indeed. On the other hand, if the meter is bad to begin with, no amount of compensation can do it much good. The remarks of the author on transient phenomena are suggestive, and a paper on this subject would be welcome. In general the methods of protection which he proposes should be very useful to existing undertakings where special provisions cannot readily be made ; but I think that much more general methods should be adopted in new systems. The schemes proposed by Whitaker and McColl seem to me to be worthy of the closest investigation in this respect.

Mr. A. E. McColl : The methods which the author advocates, although possibly they may suffice for smaller systems or in cases where the lay-out is simple, have been tried and generally found wanting on the larger and more involved systems. Personally I do not see how any reasonable degree of protection combined with continuity of supply is possible on complicated systems without the use of special conductors. I do not mean to say that the author's methods will not find application on these large systems, but I do not think they represent a general solution of the problem. In dealing with the protection of independent feeders, leakage relays are advocated in conjunction with overload relays. The author has omitted all mention of combined leakage and unsymmetrical loading devices which give instantaneous protection against faults between any two phases in addition to faults to earth. A number of devices have been developed for this purpose and these should find a ready field of application to the cases of individual feeders and isolated rotary plant. The author advocates the delaying of the action of overload relays so that on a short-circuit between phases the energy of the system may be partially dissipated before the switch is called upon to interrupt the circuit. This is given as a good feature of the overload relay. I should think it is a distinct failing. I have always held the opinion that there is a field for an overload relay having a double characteristic, i.e. a definite or partially inverse time function up to a point, and beyond that the relay to be instantaneous in action. One such relay has been put on the market, but I am not at all convinced that the mechanical features of the device are satisfactory. I see that the author does not specially commend the "watertight compartment systems," as he designates them, owing to their inability to operate on heavy flow through currents. Some of us have been developing gear along the same lines in which the special features we have sought to emphasize are, that the devices should be operative only on the faulty section and inoperative for faults beyond the section in question. It is quite a simple matter to install devices which will operate with faults immaterial of their location. It is a different matter, however, to make them discriminate correctly on a large and complicated distribution system, and this is where the systems of protection which employ pilot wires and specially constructed cables score. The author recommends that separate current transformers be employed for operating the protective gear and measuring instruments. I must say that I strongly agree with this. On the score of economy some manufacturers are adopting the practice of putting two secondary windings on one magnetic core, one winding for the protective gear circuits, and the other for instruments. It may be desirable to strike a note of warning in regard to such an arrangement. It is generally realized among station staffs that it is not safe to interrupt the protective-gear circuits, especially where the balanced-current system is employed. What is not so well understood, however, is that it is equally disastrous to break the instrument circuits where transformers with double secondaries are employed. In this case it simply means that if one winding is broken the other winding carries double current. For parallel feeder protection the author advocates the employment of overload and leakage relays for the end adjacent to the source of supply. It seems to me that this parallel feeder arrangement may be fully protected by employing interlocked discriminating relays which give instantaneous protection with faults either to earth or between phases. The only difference is that lower values of resistance are required for the earthed neutral in the case of the former arrangement. Time-lags are suggested for leakage relays on parallel feeders, but this should not be necessary. We can retain the instantaneous nature of the protection for this class of protective gear by interlocking the leakage relays so that if the faulty feeder carries the larger share of the fault current the relay operates instantaneously to disconnect this feeder. Whereas, if the fault current should be equally divided between the pair of feeders the leakage relays remain inoperative until the reverse relay clears the faulty feeder at the

remote end, when, of course, the leakage current appears in one feeder only and the relays discriminate to disconnect at the source end also. I admire the author's ingenious arrangement shown in Fig. 11 to obtain a flat characteristic for the relay down to fairly low potentials across the pressure coil. I have obtained somewhat similar results with reactive-type relays without the compensating winding. It is mentioned that this relay can be made to operate with heavy forward current, and I presume the author refers to the transformer action between the current coil and the compensating winding which would be obtained with heavy current and low potential. It seems to me that this is hardly a desirable feature, and the difficulty could be overcome by a slight change in the connections. Transformers protected by Merz-Price gear should not be disconnected by the charging current when switched into circuit. This can be taken care of by simple means without resorting to fuse-shunted relays. I agree in regard to the good features inherent in devices operating on the biased principle, and one solution of the problem is shown in Fig. 10. In this arrangement the biasing or pulling-off action is performed by a coil of the open plunger type whose pull will increase roughly as the square of the current. The operating torque for the relay is given by two quantities which may move in diverse directions under severe emergency conditions. It seems, therefore, that the bias might increase under these conditions to a value which is actually unsafe. It would be interesting if the author could say what the percentage bias would be at 30 times full-load current with the potential at 2 per cent of the normal. This refers to a relay with a normal bias of 10 per cent at full potential. I am in agreement with the author on the best connection to be adopted for reverse relays, and I should say that any other than that advocated on page 398 is distinctly unsafe. In the past the difficulty was to get the relay to stand up to heavy forward current of low lagging power factor. This usually resulted in such a large relative shift of the potential and current vectors that the relays would operate incorrectly. The connection advocated by the author, however, can be made perfectly safe for this condition, particularly for feeder protection, as usually the faults demanding the largest current are copper short-circuits which will give a fairly good power factor. Faults involving portions of a transformer winding will not be so severe, but will be accompanied by much lower power factor. The reverse relay in its usual form is advocated as the best means of protecting generators and transformers. I am afraid I do not agree with this. The reverse relay demands for its operation a plurality of plant on the busbars to give the necessary reverse flow. It is equally necessary that the protective device should operate in the case of a fault, even should there be no reverse flow possible. The purpose in this case is to obtain disconnection of the field circuit, so that an end may be put to the continued destruction of the windings. Disconnection in a case like this is possible only with the differential system. Take the case of a short-circuit between phases; the reverse relay requires that the whole internal energy of the faulty machine be concentrated on its own destruction before a reversed flow can ensue. The differential system, however, can operate while the flow of power is still in the forward direction, and consequently with a minimum expenditure of energy at the fault point. I may say that biased differential systems of generator protection are available, capable of operating with less than 2 per cent fault current and which have the required stability with heavy faults on the distribution system. Fault-settings of this order will protect against all earths close up to the neutral point, with moderate values of the earthing resistance. Systems of generator protection have recently been developed which employ directional relays and which combine the functions of the differential system with the usual characteristics of the reverse-current relays. This system is on the market now and particulars should soon be available. I am again in agreement with the author in regard to earthing the neutral through a resistance. If pure reactance is employed, the phase-shift with faults to earth may be sufficient to render the reverse relays on the faulty feeder of a pair of parallel feeders inoperative. The method of earthing shown in Fig. 20 is preferable to the usual arrangement wherein the neutral point of one generator is earthed. I should suggest, however, that the resistances R_1 and R_2 be reactive instead of ohmic, as this would effectively choke the triple-frequency currents and at the same time cause very little phase-shift in any fault current which would flow to earth. With the author's schedule of minimum current in the earthing resistances I do not agree, particularly with that referring to parallel feeder protection. In the case of a pair of parallel feeders a fault in one feeder close up to the remote end will usually operate the protective device of that end first. The sound feeder, therefore, will carry 200 per cent of load. If we wish to have any discrimination between the relays at the power-supply end sufficient to bring out the switch of the faulty feeder first, it is evident that we must pass through the earthing resistance something more than twice the full load of the feeders. This minimum current instead of being 80 per cent, as shown in the schedule, should, I think, be about 300 per cent.

Mr. E. Seddon: The author covers very much the same ground as did Mr. Wedmore in his 1914 paper, with the exception that the author favours protective schemes without the use of special conductors, whilst Mr. Wedmore advocated the Merz-Price or split-conductor system. The question of protection is very much bound up with the design of switchgear, and the tendency is to make larger switches to deal with the maximum short-circuit current likely to be interrupted from super-power stations. I sometimes wonder if we are proceeding along the correct lines. Considering the short-circuit currents possible with the very large power circuits of to-day, would it not be better first of all to limit the flow of current by quickly opening a circuit breaker across which is connected a reactance permanently in shunt with the oil switch, afterwards cutting out the faulty circuit by a second switch placed next to the busbars? The latter switch would also operate direct on single-phase leakage. As will be seen, this entails two oil switches in series,

but with such an arrangement we might be able to get something like standard switchgear. The author has set out very clearly the application of leakage, overload and reverse protection for a complete transmission system, but I am afraid that a good many engineers will not agree with his conclusions. For independent feeders I agree with the author that leakage protection as shown in Fig. 3 is the best arrangement of present-day practice, except that I prefer the fuse-shunted solenoid to mechanical movement of dashpots. My experience has been that troubles on time-limit fuses are more often traced to faulty contact clips than to the fuse itself. If manufacturers would arrange the contact pressure on the ends of the fuses instead of at the sides, the clips would not be over-strained in placing the fuses in position. The protection of closed feeders is a different proposition. It appears to me that the best arrangement is to protect all closed feeders independently of any other feeder, which can be done by either Merz-Price or split-conductor protection. The latter is preferable in all but very short feeders. In short feeders there is a possibility of the cable resistance being lower than the contact resistance of one of the split switch contacts, in which case the circuit will be unbalanced. The Merz-Price would be more suitable in this case. The methods provided for the protection against overload are much more drastic and have not the refinements of the leakage devices, and I submit that the flow of current should be limited in value before a faulty circuit due to a short-circuit between phases is opened. The author on page 405 refers to the possibility of high voltage being induced in exciter windings. I have experienced this on one or two occasions and I consider that the practice of adjusting exciter brushes when a turbo set is on load should be condemned unless an insulated stool is provided. In the event of a short-circuit in the alternator, extremely dangerous pressures may be induced in the exciter circuit. I should like to know something more about the carbon resistance. The author states that this resistance is capable of being run to red heat without damage. About 10 years ago I made some rough tests on this type of resistance in series with a horn arrester and found that when the carbon became heated, the powder was blown out of the slots. There is also another question about this resistance and that is the collection of dust. As dust cannot be cleaned from the top of the powder I should like to ask if the collection of dust will have any effect on the resistance of the powder after long periods.

Mr. J. N. Robertson: On page 392 the author refers to definitely limiting the time of opening a circuit. It would be more advantageous to open a circuit as quickly as possible and it seems to be a question of switchgear only. There was a heavy-load fault yesterday on a short-circuit, which was cleared by overhead leakage protection gear with busbar and time-limit, when it was on a ring main and synchronous motor. Had that fault remained on for any appreciable time it would have shut down half the system.

Mr. A. P. Robertson: I am certainly in agreement with bringing out the switch and opening the circuit as early as possible if there is any fault. The author in his opening remarks mentioned that the paper was primarily for those engineers who could not afford to put in very heavy switchgear. It is not necessary to spend a great amount, because I have seen a fairly cheap switch opening upon a short-circuit at 6,000 volts and although some of the oil was blown out of the tanks the switch was practically undamaged and after touching up the contacts with a file it was put in commission again. It is therefore not necessary to go to any great expense on switchgear for a small plant, and from that point of view I think we should concentrate upon getting a maximum speed of opening, especially with a system where a lot of synchronous machinery is running. It is absolutely necessary that a fault should be cleared instantly, otherwise the whole plant falls out of step. With regard to leakage protection, that ought to be instantaneous with the exception of the leakage protection upon rotary converters, especially those employing tap starting. When switching over to the running position, the leakage relay sometimes acts owing to out-of-balance caused by all contacts on the controller not coming together simultaneously. This can be got over by introducing a time-limit by means of a very light fuse. Leakage is then not instantaneous but very nearly so, as the fuse is very light. With regard to time-lags, the diagram on page 399 shows the protection of a system comprising two generating stations and four substations. If a fault occurs on the right-hand leg, there is a reverse relay operating at $\frac{1}{2}$ second from the second substation, which brings that leg out. Then there is one at $1\frac{1}{2}$ seconds at the generating-station end. This means that after the fault is clear on the one side, energy still flows for another second into this fault. With an inverse induction relay, of course, that time might be cut down. I prefer a solenoid relay with a fuse, and I think the time-limit fuse is reliable if the fuse is examined at intervals and changed occasionally. In some districts the atmosphere has a detrimental effect on the fuses, which perish and blow at less than normal current and perhaps under full load. The case mentioned by Mr. Seddon, of fuse contacts being faulty, need not arise if they are examined occasionally. The author describes various methods of tripping switches, one method being to take current direct from the transformer through the solenoid. That is a good method, but the author mentions that perhaps too much current may flow through the trip coils. I have never had any trouble from this cause. The battery system is one of the best, but it is necessary to discharge accumulators occasionally and we might be unfortunate enough to have a fault when the accumulators were discharged so that there might not be enough energy left to trip the switch. All battery tripping-systems require examination and, if properly looked after, I think are quite reliable, although there is always the chance that a fault might occur after an examination of the battery, but this is a very remote contingency.

Mr. H. V. Henniker: The title of the paper and the author's preliminary remarks tend to prevent any discussion of the relative merits of simple relay systems and the later developments in protective devices of the balanced kind, and this I think is unfortunate because

those very problems to which the author alludes in his opening paragraph call for a full investigation of relative merits. As systems extend and are linked up with other systems it becomes increasingly essential to employ sensitive and reliable protective devices, because the results of not clearing a bad fault within a reasonable time become more disastrous. Such results may entirely alter one's ideas as to what true economy is, and in fact I am one of those who believe that in such a case one cannot afford to study economy, and that to all intents and purposes there are only two factors which enter into the case at all, namely the maintenance of continuity of supply, coupled with the reasonable assurance that a faulty section will be cleared within a minimum of time. At the same time the author is to be congratulated on having shown what can be accomplished by a system of ordinary overload, reverse and leakage relays. I doubt, however, whether even he would advocate the wholesale use of such arrangements, though there are certainly sections, even on large systems, where simple relays give sufficient protection. Many of the combinations of relays described are certainly not new; for example, that shown in Fig. 3 is apparently the simple core-balancing method with leakage protection, which was in extensive use when I was engaged upon this class of work some years ago. Would it not, however, be better practice to employ three overload relays in addition to the leakage relay in the common return, since the setting of the overload and leakage relays will probably differ considerably? If leakage protection is not used three overload relays will of course be necessary with the neutral earthed. I should like to ask the author's opinion as to what in general may be taken as a reasonable leakage current to allow on a feeder before tripping. Would he consider 5 per cent of normal full-load current a suitable figure with instantaneous tripping when that amount is reached? I cannot agree with his views on fuse time-limits, which I consider preferable to either air or oil dashpots for solenoid relays. Fuses, however, certainly do deteriorate, and it is good practice to make the periodical replacement of fuse time-limits a regular part of the routine maintenance of protective gear. Despite this, however, I should place more reliance on a fuse than on a dashpot. I am glad the author deprecates the use of relay current-transformers for operating measuring instruments. Such practice cannot be too strongly condemned, not only because the measuring instruments may be interfered with, but because the relay circuit may be interrupted due to a fault within the instrument.

[The author's reply to this discussion will be found on page 636.]

South Midland Centre, at Birmingham, 17 March, 1920.

Mr. G. Rogers: This paper contains a lot that is old and well known, but there are one or two new features of great interest, particularly the design of the reverse-current relay. The leakage and overload protection of a feeder shown in Fig. 3 and Fig. 17, seems to be, where the neutral of the system is earthed through a resistance, an almost ideal arrangement for a single outgoing feeder or for a consumer's supply. The author deprecates the use of fuse-shunted solenoid protection. For a simple circuit in which a discriminating time-lag is not required, this type of protection not only is the simplest available, but is perfectly satisfactory in operation. Air dashpots are not always satisfactory, and where the fuse-shunted solenoid cannot be used the induction-pattern inverse time-limit overload relay with separately adjustable current and inverse time-settings is undoubtedly the most satisfactory instrument to adopt. With reference to the author's tilt at the split-conductor system, it would certainly not be advisable to rely entirely on the split-conductor relay. Overload relays should be put in circuit at both ends of the feeder if it is possible for current to pass through the feeder from either end. This provides a complete system of protection, which is equally as good as the combined leakage and overload relay suggested by the author. The suggestion for the protection of parallel feeders with differential reverse relays is interesting, but since there is always the danger of an unbalanced load in the feeders, this method, even allowing for the bias obtained as indicated in Fig. 10, is not likely to have a very wide application. In large distribution systems where the busbars at the generating station are protected by group reactances, and feeder reactances are installed, it is quite possible for parallel feeders to be unequally loaded to an amount beyond the control of the relay adjustments. Another objection to this system is that, in the case of two feeders in parallel, it would be quite impossible to test the relays under working conditions without both feeders being out of service at the same time. The author's suggestion for the protection of a ring main system, shown in Fig. 15, is interesting, but since the reverse-power relays on the interconnector cable between the two substations may be called upon, in the event of one of the feeders from the generating station being tripped out due to a fault, to carry the full-load current to the substation, it would be necessary for the setting of the reverse-power relay to be very high. It is not clear, therefore, what is the advantage of the reverse-power relay over an overload relay which would operate with current in either direction. I should like to emphasize the necessity of periodical testing under working conditions of every protective device by a man interested and skilled in this class of work. Anyone who has had experience of relay circuits of any description knows the simple trifles that will render the gear inoperative.

Mr. W. Wilson: The author has given a number of interesting schemes for safeguarding electrical apparatus, and without going so far as to say that where possible the running of pilot wires would not be justified, one can appreciate the good results that would doubtless be obtained from the comparatively simple installations he has described. With regard to the need for an auxiliary switch on the breaker to open the circuit after the relay contacts

have closed it, this depends upon the design of the relay in question. For example, if the contacts are $\frac{1}{8}$ inch in width, with a travel of, say, $\frac{1}{4}$ inch, then an auxiliary switch in series would be necessary. But another pattern of relay might well have 10 times these values, when it would be quite possible and justifiable to dispense with the auxiliary switch. I should also like to support what Mr. Rogers said in favour of the use of suitable shunt fuses for affording a time-limit to trip coils, in spite of the author's condemnation of these as being capricious in their action. I do not wish, however, to defend the common porcelain-clad fuse. Its wire runs through porcelain holders, making an indeterminate contact with the latter, and therefore being subject to an indeterminate amount of cooling. Its time-limit is thus very uncertain. But a fuse-wire supported in such a manner that it does not touch its supports except at its extremities, and composed of a metal that does not expand sufficiently to permit sagging against the walls of the glass tube in which switchboard fuses are generally contained, will give a time curve of surprising regularity. Not very long ago I tested a large number of shunt fuses of different lengths and of different metals, and arrived at a design which gave almost the most perfect curves I have obtained from any electrical test. It is, however, true that the operation of a fuse depends on other circumstances than the magnitude of the overload. The most obvious of these is the temperature of the atmosphere, a fuse blowing slightly more quickly on a hot day than on a cold one. It is also the case that the conductors protected by the fuse will reach a dangerous temperature more quickly on such a day, and the fuse is therefore making a perfectly correct allowance for this factor. Secondly, a fuse that has been subjected to full load for some considerable time will blow much more quickly upon an overload occurring than one which has been carrying a light load. It will be noticed that the electrical conductors will also come to grief sooner when they are heated by a prolonged full load than if they are cool, and again the fuse has afforded sound protection when an electromagnetic device would fail to do so. The solenoid and dashpot pattern referred to by the author only gives an approximate protection, for the plunger does not begin to move until the actual overload has occurred, irrespective of the state of the cables, etc., when this overload has come on. The thermal relay (or thermal breaker) would give the same protection as the fuse, in that it would represent the conductor in its behaviour, and its condition would vary just as that of the circuit does. Does not the author consider such an instrument preferable to the other types? It is much simpler than the latter, contains fewer moving parts, is more easily adjusted, and is less susceptible to faulty use by an inexperienced operator. At the same time, both fuses and circuit breakers give excellent adjustment, the former by the alteration of the gauge of wire, and the latter by the adjustment of the sag of the resistance strip. The reasons for fixing the amount of delay should depend on three considerations: (1) On the amount of heating the circuit will stand before insulation or conductors are damaged. (2) The amount of damage permissible at the fault, due to arcing, etc. (3) The throwing out of step of synchronous machinery. The first condition, as I have endeavoured to prove, is efficiently determined by a thermal apparatus. With regard to the second, there are cases where damage at the fault is advantageous in order to enable its whereabouts to be easily found. One installation with which I have been familiar consists of an overhead line supported for 70 miles on pin-type insulators weighing 30 lb. each. These insulators gave a certain amount of trouble, and when one broke down, the custom was to continue to pass the full current through it, at the 66,000 volts of the line, until it was completely destroyed. I inspected a collection of 15 of these insulators, and the wholesale destruction suggested a time-lag of more like 8 or 10 seconds, than only 2 seconds. They certainly presented a long-suffering appearance that must have been very welcome to the patrol gang when they were searching for the trouble. This long period was permitted although synchronous machinery was concerned in the scheme. I should be glad to have the author's opinion of this method.

Mr. R. G. Jakeman: The author's objection to the use of the word "protection" does not appear to be well-founded, for, although the methods described do not protect the system from the occurrence of faults, they protect the system as a whole by isolating the faulty section. There is one point which occurs to me with regard to the single interconnector shown in Fig. 14. If the fault occurs when the interconnector is lightly loaded, the full overload current must flow into the fault before the relays will act. On page 401 the author states that the circulating currents between two machines in parallel due to hunting are very much out of phase with the voltage. Actually, however, these currents are practically in phase with the voltage, since they represent the synchronizing power, which is the power tending to pull the machines back into their correct relative positions.

Dr. G. Kapp: Engineers will be pleased to learn from the paper that protection can be obtained without the use of pilot wires. The utility of these becomes doubtful when, on account of subsidences in the ground, there is a chance of such wires being broken without the staff at the power house knowing of the breakdown. The author's methods have the merit of simplicity. They do not deal, however, with the protection of a machine from the heavy blow which the winding receives in the first moment of an explosive short-circuit. Indeed, the author, in agreement with all experts, purposely introduces a time-lag so that the circuit breaker shall not be destroyed if it can be made to open at the time when the current has reached the enormous peak shown in Fig. 5. The machine can therefore not be protected by a circuit breaker and must rely on the protection due to either inherent inductance or outside inductance, preferably both. To a certain extent this is also the case as regards heavy feeders. The grading of time-lag in the different parts of the distributing plant is the usual and natural method of discriminating according to the importance of the fault, but when such grading has to be done to the fraction of a second it cannot be very definite. If it

were possible to permit a somewhat longer time all round, the grading could be made more definite and less delicate relays, not liable to act prematurely, might be employed. This means that we have deliberately to give up any idea of using the circuit breaker in order to save machines on circuits from the first rush of a short-circuit current, and adopt for this purpose the well-known method of added inductance. This means that we must reduce the power factor of the whole system to so low a value that economical working becomes impossible. There is, however, a remedy. If we install, at the delivery end of the lines, apparatus to inject leading kilovolt-amperes we again raise the power factor, and it is this policy which seems to solve the problem of something very near absolute protection. At a first glance the proposition might seem paradoxical. At the generating end we lower the power factor by burdening the system with added inductance, and at the far end we improve the power factor by lightening the system by phase advancers or other apparatus for supplying leading kilovolt-amperes. It might be argued that we have only incurred additional expense without improving the general condition as regards protection. This reasoning would be fallacious. Let us imagine such a system established with inductance at one end and capacity at the other end of a feeder. What will happen in the case of a dead short-circuit on, say, a feeder close to the power house? The condenser at the far end will be short-circuited by the fault, whilst the inductance between the busbars and the fault will come fully into play, limiting the current to, say, 4 or 5 times the normal. If the fault remains on for even as much as 4 seconds the feeder will not burn up because of its heat capacity. There is thus ample time for the circuit breaker at the generating end to act. After it has opened, the fault is still fed from the far end if there are other feeders connected to a ring main. If at the far end there is a reverse-power relay without time-lag, this relay will come into action before any of the relays in the other feeders have had time to act, and the faulty feeder will be cut off from the ring main even before it is cut off from the busbars. In the foregoing I have assumed that the condenser is connected to the individual feeder, but that is not necessary. If we imagine it connected to a point of the ring main, or even many condensers connected to as many distributed points of the ring main, the action would be the same. The same principle could be adopted for feeders going out from substations, or even to single feeders in series as shown in Fig. 4.

Mr. W. Brew: The author's introductory remarks set out clearly certain ideals with which most power-station engineers will doubtless be in accord. If such ideals can be realized without the use of special conductors, then substantial progress will have been made and a wide sphere of usefulness opened up. Those of us whose memory goes back to the days when none but fuse protection was available for high-tension circuits will probably appreciate most of all the advantages of a thoroughly sound system of control by discriminating relays. In the light of past troubles I will point out briefly what I consider may possibly be a few weak points in the apparatus described in the paper. With regard to the leakage transformer illustrated in Fig. 2, it would seem that special precautions would be advisable either in the design or in the location of this transformer to shield it from stray magnetic fields, such as might be set up by violent disturbances upon neighbouring circuits. I think it hardly possible, however, for a fault between phases to be dissociated from an immediate fault to earth on a three-core feeder, and the simplicity of the arrangement illustrated in Fig. 2, compared with that of Fig. 3, is greatly in favour of the former. In connection with the protection of parallel feeders illustrated in Fig. 8 and Fig. 9, I do not think the method suggested can be regarded as a general solution of the problem. With two parallel feeders of equal length and section, but differing appreciably as regards inductance and capacity respectively, it is obvious that the larger share of the load will pass from one cable to the other, and vice versa, according as the power factor is leading or lagging. In the case of short heavy-current single cables also, the current distribution may be seriously upset if the areas enclosed by each pair of cables forming flow and return are unequal. With reference to the protection of generators by reverse relays (page 401), I quite endorse the author's views as to the importance of isolating the rotor circuit simultaneously with that of the stator, and, from personal observation, would put forward further arguments in support of this practice as follows: (*a*) The damage to the generator from a winding fault will probably be rectified by the replacement of a few stator coils only, as compared with complete rewinding becoming necessary should an appreciable time elapse before the excitation circuit is opened. (*b*) An examination of a generator after a fault will often reveal the fact that a high-voltage discharge to earth has occurred through the rotor body, shaft, and slip-rings. Under such conditions the operation by hand of the excitation circuit switches and gear is fraught with considerable danger. The magnitude of the triple-frequency current loss assumed on page 402 is, I think, larger than is likely to be experienced with modern plant. Even were it much less, however, the annual loss capitalized should in the case of large generating units fully justify the adoption of efficient means to eliminate it. These triple-frequency losses are not easily measured with accuracy, but it may be of interest to point out that if a generator can be run as a synchronous motor the difference between two sets of wattmeter readings will give the loss. The power required to drive the motor measured by the two-wattmeter method does not include the triple-frequency loss, whilst the power measured under the same conditions by the three-wattmeter method with pressure coils connected to the neutral point does include it. In conclusion, I would strongly urge that one most important feature of a relay control system should be its power to indicate clearly when, and where, a fault has occurred, and the steps necessary to be taken in coping with it. Under the mental stress of a bad shut-down, apparently logical conclusions may be quite misleading, and this is especially likely to be the case where the seemingly erratic action of a number of instruments and circuits

has to be interpreted. A good deal of expensive apparatus has been installed and "tied up" in the past on this score alone.

Mr. A. T. Thurman: The arrangement shown in Fig. 16 for the protection of a system comprising two generating stations and four substations is all right provided the interconnector between the generating stations is large enough to transfer load from one to the other in case of trouble at either station. Part of this load may be taken up on the ring main passing through substation SS_4, in which case relays R_5 and R_{11} would operate on reverse current. Overload relays would be more suitable at these points, and to a lesser degree at the other substations. With regard to the checking of relay settings, I have found the method shown in Fig. 26 to be quite satisfactory, but the initial test after the relay has been installed in its working position should be from the primary side of the current transformer; every connection is then tested from

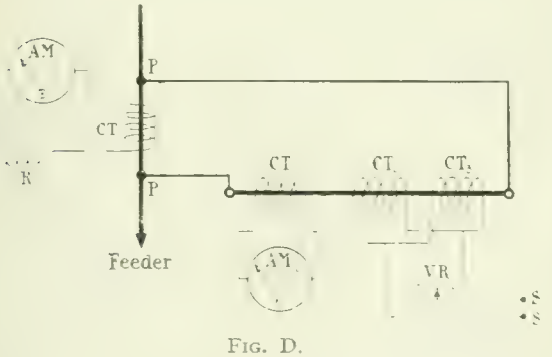


FIG. D.

the transformer to the relay. Of course a heavy current is required if the transformer is tested from the primary side, but this can easily be got by using two or three spare current transformers to step up to the required current. This method tests the current transformer, relay and wiring, practically under working conditions. The arrangement is shown in Fig. D, where R represents the relay coil operated off CT current transformer, through ammeter AM_1. CT_1, CT_2, and CT_3 are the testing current transformers, the secondary of CT_1 being connected to ammeter AM_2. Current from terminals SS is applied through a variable resistance VR to the secondaries of CT_2 and CT_3. The primaries of the testing transformers being connected to the primary of the relay current transformer at points PP. It will be seen that by this method the ratio of the relay current transformer is also tested by comparing the readings of the two ammeters AM_1 and AM_2. If no alteration to the wiring has been done after this test has been carried out, all subsequent tests may be from the secondary side of the current transformer.

Mr. J. Morton: The author has referred to the use of reverse relays for the protection of generators. These relays are usually discarded owing to their being dependent on a voltage winding. When faults occur which would put a demand on the relay to save the situation its power of action is reduced, due to any consequent drop in pressure occasioned by the fault. Nothing short of an independent supply for the pressure element of the instrument will therefore give any sense of security. It has occurred to me that such an independent supply for the pressure element might easily be obtained by installing a unity-ratio potential transformer across a reactance, the voltage obtainable being governed by the current flowing in the reactor. Further, under faulty conditions the normal current might be increased many times, thereby giving a proportionate increase in the pressure across the terminals of the potential transformer, with a resultant increase in power for the satisfactory operation of the relays. It may be said, however, that such a scheme could only be considered in cases where reactors were installed. On the other hand, we can at the present time obtain turbo-alternators having high internal reactance, and sufficient to take care of the alternator itself against short-circuits. If such a machine, however, was on load and running in parallel with other large-sized units, and a fault happened to develop near its high-tension terminals, its inherent reactance would have no effect on the amount of current which would flow from the busbars into such a fault. It therefore seems to me that some advantage might be gained by putting half the total reactance in the machine itself and the other half external to the machine. With this arrangement there would be no difficulty in providing the independent supply suggested for the relay potential coils, but it might be necessary to install some apparatus for the purpose of cutting the unity-ratio potential transformer out of circuit at some predetermined voltage limit, say 400 volts; for, in the event of the reactor being called upon to perform the function for which it is primarily installed, the voltage across its terminals would rise to any figure between zero and full phase volts. I shall be glad to have the author's views on such a scheme and to know if anything on these lines has ever been considered by his firm.

Mr. W. E. Groves: The four cardinal points mentioned at the commencement of this paper require a limitation of the number of protective devices employed. (1) The maintenance of supply is closely associated with simplicity of apparatus. (2) Apparatus although individually simple may become complex in combination. (3) The necessary flexibility involves much skilled labour for adjustment when conditions of distribution are altered by extensions. (4) Maintenance, testing and frequent adjustment by experts are costly. These considerations make the lay-out which is described more applicable to undertakings of moderate size than to large systems. The advantages of an earthed neutral have practically passed beyond the region of debate, and probably no further argument in its favour is needed. I would, however, mention that with an unearthed neutral a fault on one phase only may remain for a considerable time, ultimately developing a complementary fault on another phase and on an entirely independent line. These faults between phases, simultaneously pulling two lines out of commission, may occur at a very inconvenient time, and it is not possible to locate a single-phase fault quickly without resorting to earthing. A weak spot which will not stand the extra strain imposed by the

original fault is of course better disclosed, but not when one is occupied with another breakdown. The author mentions that the Merz-Price system operates in watertight compartments, individual sections of mains but not the busbars being protected. The system can of course be extended to cover any mains or gear but introduces complexity. In connection with closed ring mains I devised an adaptation of Merz-Price protection to cover a complete consumer's sub-station and the adjacent length of main. In order to reduce the amount of apparatus, overlapping current transformers were proposed, but even this modification did not make the scheme worth pursuing, and events have proved that it would not have been justified. For mains laid under favourable conditions it is illogical to protect cables and leave the more vulnerable switchgear unprotected. As regards open ring mains, there are several good and obvious reasons why under certain conditions of distribution they should remain open. It has been said that better use is made of the copper if a ring is closed, but even when normally closed sufficient copper should be provided to permit of all consumers on the ring being supplied from either end in case of need. Assuming therefore that a ring main is open and sections of mains between consumers are in simple series, it would not be practicable, or make for certainty of supply, to employ graded protective devices throughout where many consumers are connected to the ring. Provided the best cables and switchgear are installed, these should be given a chance and protection limited to the supply ends and the consumers' installations.

[The author's reply to this discussion will be found on page 636.]

North-Western Centre, at Manchester, 23 March, 1920.

Mr. H. A. Ratcliff: This paper deals with a very difficult subject, and I am sure the author will agree with me when I say that the various ingenious devices described do not constitute the final solution of the problems involved. I do not propose to offer a solution, and will content myself with saying that the essential thing in gear of this description is absolute simplicity. There must be the minimum amount of gear; it must be simple, and its effects must be assisted by adequate sectionalizing of the system. The title of the paper is "The Protection of Alternating-Current Systems . . ." and the author deals with feeders and distributors indiscriminately. In that connection I am reminded of a remark made by Mr. Pearce in a discussion before the Institution some four years ago, when he drew attention to the fact that the line of demarcation between high-tension feeders and distributors was rapidly disappearing. I quite agree that such is the case and I think it is unfortunate, because from it arises half the necessity for protective apparatus. It is simply a case of history repeating itself. In the early days of low-tension systems, and of the internal wiring of buildings, the same confusion between feeders and distributors arose; but the distinction had to be clearly recognized before it was possible to extend such systems to any appreciable extent. The same distinction will eventually have to be recognized in the case of high-tension systems. At the present time "high tension" usually implies something between 5,000 and 10,000 volts, but in the majority of cases economic conditions will soon require these to be regarded as quite moderate pressures. That will be a very good thing because it will simplify the problem to some extent when pressures are raised—as they will be—to anything between 20,000 and 60,000 volts. New extra-high-tension mains will be laid and will be recognized as simply feeders. The present high-tension mains will then become distributors. This arrangement will facilitate the sectionalizing of the several portions of the system, and the use in a very simplified form of some such devices as those described in the paper. The author states that pilot leads do not provide the general solution of the problem of cable protection, and I quite agree; but although not an advocate of pilot leads I think, at the same time, it must be admitted that they provide the most complete and definite solution, having regard to such apparatus as is available. Of course, the main objections to such a system are the necessity for laying pilot leads—where they do not already exist—and the fact that the pilot leads themselves are mechanically weak and just as liable to be damaged as the cables, perhaps more so. However, they are very effective and are always useful things to have on a cable system. With regard to the author's four cardinal points, I agree with him that No. (1) takes precedence of everything else. The maintenance of continuity of supply is the first and foremost consideration. It is perhaps not always appreciated that in view of the tendency towards reduced working hours the value of time will be very greatly increased. The question of continuity of supply consequently becomes of very much greater importance with the reduced working hours, and a shut-down for only half an hour is a very serious matter. Continuity of supply must therefore not be sacrificed for some slight gain in efficiency as it is the more important consideration of the two. "Simplicity of the apparatus involved." I quite agree with that, but I cannot altogether agree that the apparatus which the author describes fulfils that requirement. "Adaptability" is a very important feature and really constitutes the key to the whole problem of protection, since the main difficulty arises in connection with the application of protective devices to existing systems. The fourth point I cannot quite understand and I shall be glad if the author will explain it in his reply. I think the tone of this paper, as of others on somewhat the same subject, tends to perpetuate the false impression that the cables are the weakest link of a system. I do not agree with that at all. A well-made cable, well laid, and with sound joints is one of the strongest links on a system if due attention is given to periodical maintenance testing; and, in fact, much of the so-called protective gear constitutes a very much weaker link than the cables. If cables are abused that is a different

thing altogether. If they are overloaded to the extent of 100 per cent, they will give trouble; but if they are well laid, and are not abused, they are a strong link. I have had considerable experience of the maintenance and repair of protective gear of one sort or another and from what I have seen of it, and from the troubles which I know occur in connection with its use, I have more faith in cables than in protective gear. The various devices such as reverse relays are very delicate, and they require considerable skill and experience in their erection, and subsequent adjustment and maintenance. I think much of the time and money spent on protective gear could be better employed in other directions, and the return for the labour and outlay would be just as satisfactory from the point of view of maintenance of supply. The author refers to potential transformers. With all due respect to the manufacturers, potential transformers are notoriously the weakest link on a system, and although they may be quite suitable for operating instruments and meters, I should not like to think that the safety of a system was dependent upon the reliability of such a transformer. Protective gear has been most extensively used on systems where there are overhead lines, and I agree that they do require protection. It is also significant that protective gear has proved to be most desirable and effective on systems where it is not at all unusual to overload the cables very considerably. The effective protection of a modern system presents no very great difficulties, but in the case of an old existing system it must necessarily —as the author points out—be more or less of the nature of a compromise. Unfortunately it is the old, badly jointed, and much interlinked systems that require the most complete and elaborate system of protection. It therefore becomes a question as to whether it is the better policy to spend a lot of money on protective gear—which when all is said and done is only intended to make the best of a bad job—or whether it is better to tackle the whole matter thoroughly by cutting out the bad work and improving the lay-out of the system. This again is a case where the eventual employment of extra-high-tension feeders distinct from the high-tension distributors will greatly facilitate the work of improvement. I have never known a case where a sound, well laïd, and well jointed cable broke down from the inside, and such a breakdown is invariably the result of obvious constructional defects or bad jointing. Most breakdowns originate from the outside, usually as the result of mechanical damage. I consider therefore that the "Beaver" test-sheath provides an excellent form of cable protection, and it has the further advantage that it does not wait for the fault to occur, but gives warning that such a fault will arise in the distant future, thus giving ample time for necessary repairs before any actual operating trouble arises. If it were possible to provide all cables with such sheaths and to carry out systematic periodical insulation tests on them, that is to say, if the necessary time were devoted to making such tests instead of to the work of setting relays and so forth, serious cable breakdowns would be of very rare occurrence. With reference to the question of time-lag, the author says on page 393: "It may be stated without fear of contradiction, that more interruptions of supply are caused by opening circuits prematurely than by leaving a fault on the system for too long a time." I wish he would amplify that statement, because it is not clear to me to what sort of faults he refers. If there is any appreciable dissipation of energy at an earth fault it very quickly develops into a short-circuit, and therefore the sooner it is off the system the better. With regard to the operation of automatic switches, the claims of manufacturers are usually unduly optimistic; for, taking into consideration that first the fault relay and then the trip mechanism has to operate, it is unlikely that the average switch will break the circuit in much less than $\frac{1}{3}$ second. If time-lags must be employed I would suggest that 2 seconds be regarded as the maximum permissible limit. I have had some experience of "pyro-electric" resistances in various forms and have not as a rule found them reliable; certainly they are much inferior to metal resistances. It is not necessary that an earthing resistance should have a negative temperature coefficient, and although all pure metals have a positive coefficient, there are many thoroughly reliable high-resistance alloys which have a quite negligible coefficient over a wide range of temperature. A star-wound transformer having a closed delta winding provides a satisfactory alternative to the zig-zag earthing transformer referred to in the paper. I should like a little further information concerning the arrangement of relays shown in Fig. 10, as the operating conditions are not quite clear. There appears to be an operating force which is proportional to the current, and a controlling or retarding force proportional to the square of the current. Consequently there would appear to be some value of the operating current at which the forces become equal. The resistance shown in parallel with a current transformer is not a very satisfactory arrangement; such resistances are frequently of the pyro-electric type, and are therefore somewhat unreliable. A transformer so protected is not particularly suitable for operating instruments. I think the same amount of protection would be afforded to the transformer, and also to other apparatus in the circuit, if series choke coils or something of that sort were used. The author refers to the operation of balanced protective gear caused by current-rushes when large transformers are switched into circuit. Several cases of this nature have been brought to my notice, and there has frequently been much speculation as to why the protective gear operated. I am therefore glad to see that the author practically confirms my views regarding the nature of the occurrences. When trouble arises on a system it is usually the unexpected that happens, and that one fact alone is sufficient to make the problem of adequate protection very difficult.

Mr. G. A. Cheetham: I feel that this paper is an attempt to overcome a difficulty, and I suggest that this difficulty is not the use of special conductors for protective purposes but the fact that such systems were evolved at a rather late stage in the development of the art when a large number of transmission schemes

were already in existence. In most cases the cost of converting these schemes to the new method was prohibitive, otherwise I have no hesitation in stating that the great advantages possessed by the new methods would have ensured their adoption. The very fact that in spite of this handicap the newer systems have been used on the extensions to existing transmission schemes, seems to prove the existence of a regret in the mind of the operating engineer that they were not in existence when his transmission system was first designed. It certainly establishes the fact that these systems possess undoubted advantages over those previously installed. The introduction of special conductors is only required for fault discrimination; a perfect system can readily be designed without such conductors where discrimination is unnecessary. For example, a single feeder is completely protected by core-balance and overload relays. The introduction of other feeders is the point where controversy commences regarding the system of protection to be adopted. The main advantages of such systems as the Merz-Price and Merz-Hunter consist in the speed with which faulty apparatus is removed from the mains, and the ready adaptability of the systems to most portions of a network. The author appears to consider the former to be a rather doubtful advantage. I can only agree that there is a considerable danger in disconnecting apparatus too early when that apparatus has not itself developed a fault but is merely disturbed due to a fault at another portion of the network. If it is definitely established that a fault has occurred, then disconnection should be as rapid as possible to prevent further development of the fault. It should also be borne in mind that whilst an earth fault may remain on a transmission scheme for a considerable time without threatening the continuity of supply, the earthing resistance does not ensure that the particular portion of the scheme affected does not carry a heavy overload. I am therefore not in favour of retarding the operation of leakage relays. A recent example illustrating this point was brought to my notice in which an examination of a machine after the operation of the Merz-Price gear revealed a single pinhole in the winding. I fail to see why the addition of fuses in the pilot wires of Merz-Price apparatus slows down the operation of the apparatus on the occurrence of an earth fault. With reference to the adaptability of protective gear to various portions of a network, I have been impressed with the diversity and complexity of recent developments in protective devices taking place in America where the underlying principle is the differential scheme as outlined by the author. As the system grows, the interlocking necessary to provide for the changed conditions occasioned by the tripping of a breaker becomes complicated. The "watertight" compartment principle of the Merz-Price or Merz-Hunter schemes which the author mentions is here a decided advantage, as it enables a ready step-by-step extension without further complication. With reference to the carbon earthing resistance, great care should be taken that the value of the earthing resistance of this type is so arranged that sufficient current passes on an earth fault to trip the protective gear immediately, otherwise there is a danger that a large time-lag may be introduced before the fault is cleared. I wish to support the author's opinion that protective gear connections should be kept entirely separate from the instrument connections, as the added complexity widens the pitfall into which far too many persons fall already and who usually excuse themselves by maligning the apparatus.

Mr. J. S. Peck: In the early days of power distribution there were two schools of distribution engineers; one believed in installing all the protective devices that the manufacturers could suggest, the other in using no protective devices at all, except for overloads. From the claims made, it was very difficult to tell which school was the more successful, but I think the general opinion was that those who had least protection had the greatest continuity of service. But as generators and systems have grown in size, and as networks have increased in length and complexity, it has become increasingly necessary to provide protective devices in order to limit the extent of the damage when a breakdown occurs. In this country the so-called discriminating protective systems (Merz-Price, etc.) have been very extensively developed, while in America they have trusted more to the graded time-limit system of protective relays. I think most operating engineers are sceptical of the relay as a method of protection, as it has a reputation for working when it should not, and for failing to work when it should come into operation; but certainly there have been great improvements made of recent years in protective relays. The author states that the leakage current to earth can be limited by the amount of resistance in the earth connection. This is only partially true, as the charging current on the system has a very great effect in determining the amount of current which flows to earth at the fault. I remember that some years ago when discussing this subject, Mr. Pearce or Mr. Mackenzie stated that at one time when they were running with a free neutral, and where the amount of cable connected to the Manchester system was comparatively small, they were able to run for several minutes with a cable fault to earth, but as the amount of cable connected to the system increased, the charging current became very large and an earth would develop into a short-circuit between phases in a very short period of time. Thus no matter how much resistance is put into the earth connection, the charging current of the system will flow to earth at the fault. The author referred to the protection of generators, and Mr. Cheetham also touched upon that point. If we are to reduce to a minimum the risk of fire in a generator in the case of breakdown, it is necessary to disconnect it instantaneously. The more rapid the disconnection, the less chance there is of a fault developing into a conflagration. Reference has been made to the high temperature coefficient of the cast-iron earthing resistance. I believe I am correct in saying that cast iron has a very small temperature coefficient. Steel has a very high temperature coefficient. I do not quite understand the statement that with a reactance in the earth connection the neutral point is at a higher potential above earth than is the case with a resistance.

With either a reactance or a resistance, a certain current corresponds to a certain drop across the reactance or the resistance, and this drop represents the potential of the neutral above earth.

Mr. H. Hawkins: As a distribution engineer, I am naturally much interested in this paper, and have a further interest as joint originator of a protective system which does employ special conductors. One of the conclusions I have come to after reading the paper is that judging by the fact that the consideration given to short-circuits largely predominates over that given to earth faults, the protective systems outlined by the author apply mainly to overhead or railway systems, which of course limits its scope. Manchester experience differs considerably so far as the type of fault is concerned. As the author refers to the Merz-Price and Merz-Hunter systems, I should like to bring to his notice the system for which I am in part responsible, and of which this is the first public mention. Starting with Mr. Pearce's maxim "that a feeder at the main generating station should not be automatically disconnected except in the event of a fault to earth on any one of its three phases," and with that end in view an endeavour was made to find an absolutely selective system, embodying these four qualities, simplicity, adaptability, rapidity of action, and stability. I think it will be agreed that if a protective system be found embodying these four points, continuity of supply would follow as a natural consequence. By a process of elimination the Ferranti-Field transformer with relay was arrived at as the most stable type of protective gear; these transformers and relays installed at each end of the feeder it is desired to protect, with pilot wires or special conductors joining the secondaries together, constitute the invention. I suggest that if the four points I have mentioned are obtained absolutely there is good argument for the use of pilot wires. The author admits the possibility that they may be desirable unless their use is precluded by special conditions. I take it this may be an argument in favour of the laying of pilot wires with future cable extensions. In my opinion pilot wires may in themselves have other and distinct uses, and more may arise in the future. Admitting the desirability, in view of the above, of some connecting link other than a feeder and telephone cable, the addition of the extra cores for the protective system is not a serious problem. I would say further that pilot wires are in my opinion the only known means of obtaining an instantaneous evaluation of the conditions prevailing at each end of a cable at any moment, with simultaneously co-ordinated action or inaction as the occasion demands. One of the points laid down as desirable is simplicity. Feeder protection primarily is a distribution engineer's task; it is his business to avoid complicating the feeder cable or burdening the power or substation with extra instruments or gear introduced into the high-tension circuit. The author states on page 394 that the Merz-Price and split-conductor systems are worked in "watertight" compartments, and I agree with a previous speaker that this is an advantage. If the feeder protective gear can be depended upon to act selectively, neither influencing nor being influenced by other gears, in the event of a shut-down early indication is given as to where the trouble lies. The author admits that the use of current transformers for a dual purpose is not desirable, which I think is a concession to the "watertight" idea. With regard to adaptability, Ferranti-Field transformers with pilot wires can claim it to a high degree; it is capable of dealing with any of the systems of feeders selected by the author or could be applied to either side of step-up and step-down transformers. With regard to rapidity of action, I certainly claim that the Ferranti-Field transformer with its relay is one of the quickest acting gears at present in use. The author admits the extreme importance of clearing faults instantly under certain conditions, and I am inclined to lay it down as an axiom that on feeders an earth may develop into a short-circuit, but a short-circuit will develop into an earth. I agree with other speakers that feeder faults should be cleared as rapidly as possible to prevent the ill-effects mentioned by the author on page 391 as likely to happen if a fault is left on the system. I would point out further that rapidity of action of feeder protective gear has within my own personal knowledge prevented possible bodily injury in several cases. As an instance of rapidity of action of a Ferranti-Field transformer, I would mention that having once accidentally earthed a feeder carrying 2,000 kw. at a works within a mile of Stuart-street power station, a spark no greater than that made by striking a match was the only result at the point of contact, and it was not until I heard the works shut down that I realized that the feeder had tripped out. At the time there was about 45,000 kw. of generating plant connected to the busbars. I have known other cases where live feeders on the network have been earthed and cleared by the Ferranti-Field or balanced-transformer method of protection where those responsible for the accidental earthing have not realized until advised from the power station that the gear they assumed to be dead was actually alive, the feeder having tripped out. Furthermore, before quick-acting protective devices were used distribution engineers were put to considerable trouble and much time was lost, as severe damage to a cable by heavy and prolonged fault currents prevented accurate and rapid localization. With regard to stability, any system which is normally inert such as the Merz-Beard referred to on page 401, or the Ferranti-Field with pilots, appears to possess decided advantages over those using balanced pressures or currents, as there is no stored-up energy in the secondary circuit the equilibrium of which is liable to be disturbed by pressure or current surges, or by reason of the differences which may exist in the realitive values of the impedances of the cores of a cable or its connections, which differences may be largely accentuated if very heavy currents are passing. In conclusion, I am inclined to think the author has attempted to reconcile incompatibles, that is, a system of protection competent to deal adequately with either cable faults or those confined to the generating station or substations.

Mr. L. Romero: The author recommends on page 396 the use of the same type of differential reverse relays

at the generating station end as at the substation end of parallel feeders. It appears to me that this would be a very uncertain system of protection and almost as likely to trip the sound feeder at the generating station end as the faulty feeder. If we suppose that a fault to earth occurs on, say, C phase, on one of the feeders very near the substation while both feeders are carrying their normal load, the difference in current between the two feeders at the generating station end will not be sufficient to operate the relays until the faulty feeder has been cleared at the substation end. When this has been done the currents in the two feeders at the generating station end will be as follows :—

Sound feeder : load current in all three phases.
Faulty feeder : no current in A and B phases and the earth fault current only in C phase.

That is to say, the relays on A and B phases will operate to trip the sound feeder as that feeder is more heavily loaded on these two phases, and the relays on C phase will only operate to trip the faulty feeder if the fault current to earth is sufficiently greater than twice the load current on one feeder, or some 600 amperes in the case of two 0·25 square inch feeders in parallel.

Mr. J. Williams : Is the author satisfied that such close time-lag setting as $\frac{1}{4}$, $\frac{3}{4}$ and $1\frac{1}{4}$ seconds (see page 393) can be actually obtained in practice ? Such tests cannot be taken with an ordinary stop-watch and I should like to know whether a cycle recorder or some similar instrument is actually used for the purpose. I have tested various types of time-lag devices on much coarser settings than those mentioned above, and as a rule the errors are very considerable. With reference to Fig. 11, can the author give particulars of a reverse-current relay compensated so as not to trip on forward current ? I know of one case where trouble was experienced due to both reverse-current relays tripping at the substation. It was only after carrying out exhaustive tests that we found that this type of relay tripped on forward current, provided the power factor and pressure were low enough. For instance, it tripped under the following conditions :—

Volts	Power Factor	Relay Tripped
10 per cent	Unity	21·5 times the setting
5 ,,	,,	12 ,, ,,
30 ,,	0·2 (lag)	20 ,, ,,
5 ,,	0·1 ,,	9 ,, ,,

The importance of ascertaining the characteristics of reverse-current relays before installing will be evident from the following tests, which were carried out on reverse current on three different types of relays, A, B, and C.

Type	Pressure, per cent	Power Factor	Tripping Current as Number of Times Setting
A	5	1	5·6
B	5	1	6·5
C	5	1	20
A	5	0·3 (lag)	5·4
C	5	0·3 ,,	62

" A " trips on forward current, but B and C do not. In my opinion every effort should be made to avoid direct-current tripping (page 405), especially where batteries are required, owing to the large increase in maintenance cost. I agree that it is most important to check the relays with the current transformers (page 406), more particularly in order to ascertain if the ratio error is excessive as a result of the volt-ampere load on the secondary side being too high. I came across a case where overload relays on a feeder failed to operate, and when they were tested with their current transformers the ratio error was found to be about 81 per cent low at the full load of the current transformer before the plunger even commenced to rise. In this particular case, with 100 per cent overload on the primary of the current transformer it would not trip the relay, the setting of which corresponded to 20 per cent of the full load of the current transformer. In other words, the ratio error was at least 90 per cent. With the plunger down, it was found that the pressure drop on this relay was 35 volts on the 1-ampere setting, which corresponded to 20 per cent of the full load of the current transformer. In other words, 875 volt-ampere relays had been connected to 65 volt-ampere current transformers. Mr. Cheetham mentioned about Merz-Price protective gear isolating a fault quickly. I have come across a similar case where one of the end covers of a vertical-type generator dropped on the stator winding, causing a very slight puncture of the insulation. The Merz-Price balanced protective gear isolated the machine immediately, and the coil was so slightly damaged that it was difficult to locate the fault.

Mr. S. Ferguson : I am afraid the scheme of protective gear shown in Figs. 15 and 16 as applied to ring mains will not find favour except on existing systems where it is impossible to lay pilots or to put in split conductors. If new mains are being laid the Merz-Price system or split-conductor protective gear seems to me infinitely preferable. The employment of overload relays and reverse relays on ring mains would give the operating engineer a considerable amount of trouble. It is all right to set relays with a difference in settings of $\frac{1}{4}$ second, but then account has to be taken of variations in the time for the operation of the oil switches themselves. Unless we have identical switches, and unless extreme care were taken in setting the relays the $\frac{1}{4}$ second would be easily swamped.

Furthermore, changes in operation conditions and extensions would call for adjustments of the relays, which would become troublesome. There is one other solution to the problem of protection of existing ring mains where no pilots are laid which has been adopted by at least one of our largest public supply authorities, that is, to make the ring main solid after it has once been put in commission and to rely on overload and leakage devices at the two ends at the main generating station. Oil switches with overload and leakage devices are installed on the ring main in the various substations, but are only used for protecting the main when it is being switched in after having been disconnected for repairs or fault localization. If the overload device does not operate on closing, the switch is then locked in and all the protection is controlled from the central station. I believe this system works very well in practice, in view of the fact that only quite a small proportion of faults develop on the cables themselves, and the opening up of sections of the ring main is not required to be carried out frequently. I would not suggest that this scheme is as good as the Merz-Price or split conductor, but it is an alternative I would prefer to the system embodying such a large number of relays as shown in Fig. 16. In laying down new mains I think split conductors should be utilized. In the early stages of this protective gear, difficulty was experienced due to the system requiring a special type of oil switch with split contacts. This has now, however, become standardized and does not involve a very great increase in expenditure. With regard to the scheme shown in Fig. 8 (differential reverse relays for duplicate feeders) I think this gear can be simplified at the generating station end by the employment of the Ferranti-Waters protective gear which is generally the same in principle, the chief difference being that core balancing is employed. A ring transformer with two windings is slipped over each of the duplicate cables. One winding on each transformer is used for comparing the currents in each feeder, and the two are connected differentially, whilst the other windings are connected in series and serve to operate the voltage coils of two reverse relays. The result is that with this scheme only two reverse relays are required instead of six for a three-phase system. Furthermore, the current transformers are of the ring type and can be slipped over the main conductors, thus avoiding insulation troubles, and potential transformers are entirely eliminated. This scheme is also applicable to substations where there is an alternative source of supply, e.g. where there are three or four feeders in parallel or where there is a duplicate ring main. It is admitted that the above arrangement pre-supposes that on the occurrence of a fault there will be leakage to earth. It is difficult to imagine a fault which does not comply with this condition, and in view of the saving of relays and apparatus it is worth adopting. With regard to the method of operating oil switches on the occurrence of a fault, I think the tendency is to do away with an independent source of supply and to allow the fault current itself to operate the oil switch. By this I do not mean the high-tension fault current but the current in the secondary of the current transformer corresponding to the same. To accomplish this, oil switches must be capable of being tripped with a very small amount of power. To indicate the developments which are taking place I would point out that it is now possible to operate an oil switch from a current transformer having only 100 ampere-turns, whereas formerly current transformers of 400–600 ampere-turns were necessary. There is every probability that this figure will be reduced in the near future to 40 ampere-turns. I think it is highly desirable, wherever practicable, that the fault current itself should be used for tripping oil switches, rather than reliance be put on an independent supply which may not be available at the critical moment.

Mr. A. Stubbs (*communicated*): Contrary to the view expressed by nearly all the speakers, I am inclined to think that the author of the paper has realized what ought to be the logical treatment of this question when he refers to Fig. 3 and shows the advantage of a certain definite time-lag in the operating gear. This time-lag should at least be used wherever the generators may be considered to be feeding directly into the fault, i.e. in connection with all main feeders and the generators themselves, assuming it is possible (and it would appear to be more than possible) that a fault could develop more rapidly than the operation of a protective gear and its heavy oil switch. The conditions then are that an almost instantaneous short-circuit has developed upon the system and is fed directly with power from the generators. Where modern turbo-generators are concerned the characteristic of a short-circuit is shown in Fig. 3, only that the peak is much more pronounced and may be as much as 20 to 30 times the permanent short-circuit current. With a quick-operating protective gear and oil switch there is at least the chance of taking the peak current, probably with very disastrous consequences at the point where the circuit is to be broken. Since in the large power stations one of the limiting features is the capacity of the oil switches installed, it is hopeless to try to design a switch to take the peak current during a short-circuit; in any case it would mean unnecessary size and expense in switchgear. The proposition would appear to be therefore to wait for the permanent short-circuit current to set in and then to break the circuit with a suitable oil switch. The interval of time between the occurrence of a fault and the operation of the switch need not be very long, but depends upon the magnetic energy of the alternator rotor circuit. It is necessary to wait until the back ampere-turns of the stator have gradually decreased the flux of the rotor. A well-established rule of one of the best organized turbo-alternator test-plates in this country was: "Do not take chances," a rule which could be extended to all electrical work. Applying this, we see that if there is only the slightest chance of having to take the peak current referred to, it is sufficient justification for the use of a time-lag in the protective gear.

[The author's reply to this discussion will be found on page 636.]

North Midland Centre, at Leeds, 20 April, 1920.

Mr. W. Redmayne: I am connected with an undertaking employing an unearthed 3,000-volt three-phase system with the cables connected in "rings." We find that nine out of 10 earths are caused by failure of instrument transformers, and such earths do not always cause arcing owing to the fault current being limited by the static capacity of the cables and apparatus; they may, and occasionally do, cause pressure-rises which find a weak place at another part of the system. An advantage of the unearthed ring-main system is the ease with which a fault may be located to any particular ring main; it is only necessary to switch off one side of each ring main in turn until an alteration is observed in the indication of the static "leakage" voltmeters, and when such alteration is observed the fault can be further localized to one side or other of the ring main by switching off first one side and then the other and observing the effect on the voltmeters. This effect is caused by the pressure-drop due to the resistance of the cable to the passage of the fault current. My experience with graded time-limit relays or fuses has been unfortunate, as they have proved to be of no value in case of a severe fault. Then, again, on a ring-main system if the relays are graded towards the middle of the ring and a fault occurs anywhere on that ring main, the lightly graded relays at the middle are bound to operate. It may be of interest to the author to learn that we have installed and are just about to put into use a method of tripping without the use of primary or secondary batteries; this method makes use of both current and pressure transformers for operating the trip coils which are connected by means of a suitable relay energized from the split-conductor transformers. The connections between current transformers and time-limit fuses need careful attention; I have observed cases where the connections appeared to be short and sound but the switches have tripped without blowing the fuses, thus proving that a poor contact existed, perhaps owing to the oxidized surface of the fuse contact-clips. Relays with mercury-cup contacts also appear to be unreliable; I have several mounted on sheet iron cubicle doors and when these doors open the vibration throws out nearly all the mercury. A loss of mercury also occurs each time the relays operate and eventually the relay is rendered unfit for use. Some makers will also insist on using copper or brass mercury cups, notwithstanding the well-known creeping and amalgamating action of the mercury on such metals.

Mr. R. D. Spurr: I am very interested in the question of discriminating relays, as we have in Bradford four 6,600-volt feeders working in parallel. At the generating station we have induction-type current relays similar to those described in the paper, but at the substation, in addition to the induction relays, we have fitted reverse-current relays in order to be sure of clearing the faulty feeder only. These latter relays are not of the compensated pattern described by the author, but we are assured that owing to the length of the four feeders we shall not have trouble due to opening on a forward current. They have been in use four years and up to now only one set has been known to operate, but as no permanent fault was recorded we assumed that the fault was on a bulk consumer's premises near the substation and was not of sufficient magnitude to be noticed by the attendants. We cannot cross-connect these relays as suggested, although each pair of feeders follows the same route. The currents at any point are unequal and varying, owing to consumers taking off current from one or other of the feeders between the generating station and the substation. Current-settings are not of much value for discriminating purposes on a series of induction relays when a short-circuit occurs, though for simple overload protection the current-settings will obviously be higher near to the generating station where the current normally carried is greater. The time-setting on a short-circuit is the all-important factor, and we have definitely fixed upon 0·4 second as the smallest interval of time permissible between successive relays under those conditions. Trouble occurs on mixed systems where there are fuses and relays in series, as all types of fuses deteriorate and are unreliable unless frequently changed. To illustrate how this occurs in practice I know of a case of a failure of a 300-k.v.a. transformer operating at 10,000 volts, taking current from two 700-k.v.a. transformers in parallel at our substation 3 miles away. These transformers were protected by induction-type overload and leakage relays set to operate in 0·3 second on a short-circuit between phases. The 10,000-volt feeder and the defective transformer oil switches were protected by fuses shunting the alternating-current trip coils, and in the case of the feeder the fuses used were supposed to operate at a lower k.v.a. loading and smaller time-lag on overload than the relays. What actually happened is rather problematical, but it was found that the distant oil switch undoubtedly opened first, and the surge operated the feeder and transformer oil switches due to the timing being too close. No ill-effects were felt on the 6,600-volt system, beyond a momentary drop in voltage, nor did any of the higher set relays operate. The general adoption of fuse-shunted trip coils is undoubtedly due to the difficulty of obtaining direct current for the purpose of tripping the oil switches. I would suggest that the Fuller Block cell will be found to fulfil the requirements in this direction. The makers claim that it will retain its charge for long periods; it is comparatively light in weight, and boxes of six cells can be handled comfortably without fear of disintegrating the plates. We have a number of oil switches fitted with 50-volt trip coils dependent on one of these batteries for trip current. This is a great improvement on primary cells, as emergency lighting can be worked off these batteries in case of a failure of the supply. The railway and telephone authorities are adopting it for their intermittently working apparatus and only charge up twice a year. The author's scheme for protecting a ring main will be welcomed as an alternative to using

two existing cables as one for split-phase protection. It is undoubtedly a most ingenious method of applying reverse relays for discriminating purposes, but the question of time-setting will require careful consideration, and unless this relay can be constructed to have an easily adjustable time-setting I am afraid it will not meet with approval. The adjustable and reliable time-setting of the induction relay is a point which very favourably impresses itself upon the user. I would suggest that the two types of relay might be assembled together in one case with the trip contacts in series so that the current could only reach the trip coil when both elements had performed their allotted tasks, the reverse element the direction, and the induction element the time. The combination would perhaps result in an expensive instrument, but accurate timing and directional functioning would justify the cost. The question of disposing of potential transformers is one that does not receive the attention it deserves, and when used with reverse relays it is not at all necessary or desirable to have separate transformers for each feeder. We have one set of two single-phase transformers in open delta, protected by three Reyrolle dust fuses, to supply the current for the potential coils of four sets of reverse relays, but I am strongly of the opinion that on large systems it would be advisable to have a good oil switch for each group of potential transformers, as some of the effects of recent faults on this type of apparatus have been rather alarming. As the effectiveness of most protective apparatus is dependent upon the continuity of the earthing resistance, the question of metal grids or carbon powder depends upon which is the more reliable. Iron grids have a way of breaking occasionally, and some types of carbon-powder motor starters were not a success for intermittent use. It would be interesting to know the life and continuous carrying capacity of a Brazil carbon-powder earthing resistance, as iron grids can be worked for long periods at a dull red heat.

Mr. C. J. Stacey: I think that the time-lags in connection with reverse-current relays should be marked on the different settings with two figures: first with the time-lag at the normal tripping current, and secondly with the time-lag at heavy fault conditions, or where the time-lag is no longer dependent on the variation in current. The difference in the time-lag between the above conditions is considerable, and engineers who are considering this class of apparatus for the first time are liable to be misled, unless they are supplied with the curve showing the relation between the time-lag in seconds and the current passing through this apparatus. I do not agree with the author regarding the earthing of the star point on the primary or high-tension side of potential transformers, when used on a three-phase system with an earthed neutral, and this is contrary to Board of Trade regulations. I would point out that it is undesirable to use potential transformers connected star/star for the measurement of power, as a floating neutral is sometimes obtained which does not lead to correct measurement of power. This can be overcome by using potential transformers which are connected delta/star.

Mr. R. D. Fairclough: I was very interested to note the point raised about capacity tending to aggravate surging, as this is not always realized and on the system I was operating we had a serious case where the capacity effect undoubtedly increased our troubles, though it is only fair to state that I believe we were running our neutral connection open-circuited when the fault occurred. The effect of the surges set up was so serious that the system was paralysed for a time; the trouble extended and actually broke down the cable and sub-station system in several places. I should certainly be interested to hear more of the feeders the author spoke of, where a number of plain overload trips in series along the route acted so satisfactorily by virtue of their discriminating settings. My own experience is that one ought theoretically to be able to obtain that result, but in actual practice when a heavy fault occurs all the switches open simultaneously. This is rather borne out by the curve showing the high instantaneous value of the short-circuit current. The author deplores the unpopularity of potential transformers and says that switchgear makers ought to alter their practice with regard to these transformers; but I do not seriously think that the makers have strong views on the matter, as one can buy potential transformers for either mesh or star connection, and there are many arguments for and against each arrangement. As a general rule mains engineers dislike potential transformers on the ground that their automatic protection has to take the form of high-tension fuses, which have a disagreeable way of blowing at inopportune moments. I am of opinion that this blowing of fuses is due to surging which occurs on all systems, although many engineers appear unwilling to admit this. The surges evidently result in a rise of pressure above the saturation of the transformers, which transformers then admit of sufficient current passing through to blow the fuses, and here I agree that the makers might be well advised to consider design from that point of view. When discussing this matter with a mains engineer recently I was informed of a case of high-tension bulk supply where the meters were placed at the substation and the potential transformer fuses were constantly blowing; later on, the question of payment for cable losses was raised and by agreement the meters were placed in a meter house half way on the cable route, and after that the fuses did not blow, showing, I think, that surges occurred but (after the meters were moved) were absorbed in the dielectric hysteresis along the cable route. I myself overcame a similar difficulty by putting static tension limiters close to the terminals of the potential transformers, and this immediately stopped any further fuse-blowing troubles. The author stated that one great advantage of the carbon resistance in the neutral is that it can be run till red hot, allowed to cool and then everything is again in order, but I am afraid that I cannot agree, as my experience is that if these resistances have to carry current for any length of time they ultimately open circuit altogether. We had an interconnection through auto-transformers and as our neighbour's cable system grew in size we found that the inductance of the transformers in series with the capacity of the cable system was producing what was,

in effect, resonance and there was a constant flow of current through our earthing resistance. This, though a little disquieting, was not a serious matter after it had been investigated and diagnosed, but up to that time it affected trip settings (which were afterwards adjusted to allow for this) and caused the resistance to become overheated and to open circuit, necessitating systematic inspection and adjustment.

Mr. J. C. B. Ingleby: I should like to ask the author whether the carbon resistances oxidized when red hot and whether their ohmic resistance did not gradually alter due to this heating. The author mentioned the term "synchronous speed" in connection with the small relay motors, but I cannot understand how this type of motor can have a synchronous speed.

Major K. Edgcumbe (*in reply, communicated*): It was, I suppose, inevitable that much of the discussion should turn upon the merits of the devices proposed in the paper, as compared with the split-conductor, Merz-Price and other systems necessitating special cables, in spite of the fact that the title of the paper was "The Protection of Alternating-Current Systems without the use of Special Conductors." The task which I set myself was to show what could be done without recourse to special cables, and certainly not to draw invidious comparisons between these proposals and well-known systems already performing excellent service.

I am gratified to see that the figure of $\frac{1}{2}$ second between the time-settings of a number of relays in series is considered by several speakers to err, if anything, on the high side. Mr. Spurr states that at Bradford they work with intervals of 0·4 second with satisfactory results. Mr. Clothier gives 0·1 to 0·15 second, and Mr. Cowie, in the London discussion, gave 0·2 second, as the time taken by an up-to-date oil switch in clearing a fault; which would leave at least 0·3 second for the relays and to cover contingencies, to say nothing of any discrimination which the current-settings might afford as a further safeguard against premature tripping.

Dr. Kapp's contribution to the discussion is of considerable interest. I did not allude to the use of reactances in feeders, as that would have carried me beyond the limits of my subject, but there can be no doubt that the limitation of the value of the short-circuit current is, at the moment, one of the most vital questions, and any solution which aims at doing this without adversely affecting the power factor of the system is to be welcomed.

If there is anything in Pope's injunction to "damn with faint praise," the fuse-shunted relay or trip-coil fared badly, even at the hands of its champions, in the discussion. Mr. Seddon, for example, whilst admitting the troubles, thought that the contact clips were probably more to blame than the fuse itself. Mr. A. P. Robertson attributed the many failures to the detrimental effect of the atmosphere. Mr. Redmayne cited cases of switches tripping although the fuse had not blown, owing to bad contacts. Mr. Henniker says of fuses that they "certainly do deteriorate and it is good practice to make the periodical replacement of fuse time-limits a regular part of the routine maintenance of protective gear." A serious difficulty arises, however, in that a fuse can only be tested by destroying it and there is then no guarantee that the one put in to replace it will have the same characteristics. In view of the remarks of these and other speakers I feel that I was by no means overstating the case when I said: "A fuse is at best a capricious piece of apparatus, and for a large distribution system to be dependent upon its vagaries seems to represent very doubtful economy."

The protective scheme illustrated in Figs. 15 and 16 was criticized by more than one speaker on the ground that, whilst applicable to small systems, it was not suitable to large ones, owing to the long time-lags required for some of the relays. I would point out, in reply, that this system was only recommended by me for rings consisting of *single* feeders. Wherever parallel feeders are used (whether throughout or only at certain points of the ring) differential reverse relay protection (Fig. 8 or 9) would be used, and the time-lags of the relays on either side could be shortened accordingly. For example if, in Fig. 16, the feeders connecting $S S_3$ with $S S_2$ and $S S_4$, respectively, were run in parallel, their protective relays would be set to act instantaneously and the maximum time-lag at any point would be reduced from the $2\frac{1}{2}$ seconds shown in the figure to $1\frac{1}{2}$ seconds. On any system of moderate size a large number of points will undoubtedly be fed by parallel feeders, so that the protection of the remaining (single) feeders by the methods described on page 399 will not involve excessive time-lags.

As regards earthing the neutral point, I am pleased to see that practically every speaker takes it for granted that the generators will be earthed through a resistance. In this connection Mr. Beard took me to task for giving 40 per cent of the generator capacity as a suitable setting for the relays on the self-balancing (Merz-Beard) system of generator protection, on the ground that this figure was abnormally high. But Mr. Clothier confirms the figure I propose. He says "Merz-Price and Self-balance (Beard) generator protection are in satisfactory operation at or below . . . 35 per cent of generator capacity. But I would rather increase the minimum current through the earthing resistances." He adds "Relays are all the better for plenty of margin for operating inaccuracies." It is precisely this margin that the carbon-powder resistance affords owing to its negative temperature coefficient. The initial current can be adjusted to be 10 or 20 per cent in excess of the relay or oil-switch setting and, should the switch "hang fire" for any reason, the current increases rapidly in value and so gives a wide margin to cover any such contingency. Allusion may be made to one feature of the Brazil earthing resistance which was not brought out in the paper as it might have been, and that is the decrease of current which takes place out of all proportion to a fall of pressure at the resistance terminals. This feature is valuable in suppressing the flow of triple-frequency currents between generator neutrals. A case was recently investigated in which two generators, each provided with its own Brazil resistance, designed to pass an initial current of 250 amperes at 10,000 volts (line pressure), were found to have a third harmonic voltage of no less than 1,100 volts between neutral

points. The circulating current which would flow under these conditions with a metal grid resistance works out to about 23 amperes, whereas the measured current actually passing with the Brazil resistance was found to be only 8 amperes, or about one-third. It may be well to point out that the arrangement shown in Fig. 20 can be extended until R_1 and R_2 become the whole of the resistance, R_3 disappearing. That is to say, each generator has its own resistance, as in the case just cited. This arrangement is advantageous as regards the elimination of circulating currents, although it suffers in that the fault current to earth is dependent upon the number of generators which may be running at the time.

Mr. Romero draws attention to the fact that with parallel feeder protection (Fig. 8) the whole load current flows through the sound feeder as soon as the faulty one has been isolated at the further end, which necessitates an increased earth current. On page 405 of the paper as published in the *Journal* I have added a sentence to make this clear.

Mr. McColl alludes to relays the action of which depends upon the unsymmetrical loading of the three phases amongst themselves. Such relays are of limited application. They can be used to isolate an overhead feeder should one of the lines break, but are too liable to act on the occurrence of a single-phase fault on plant connected to the feeder to be of great value.

Mr. Wilson suggests that a thermal relay (or fuse) has the correct characteristics for opening the circuit, in that its action depends upon its past thermal history. For example, it will act with a smaller overload and with a shorter time-lag if it has already been subjected to full load for a prolonged period, which is as it should be since a given overload will damage a cable that has already been heated more than when it starts from cold. Unfortunately, the heat capacity of a thermal relay or a fuse is negligibly small compared with that of the cable, so that the extra protection afforded is illusory. At the same time, relays can be designed with a heat capacity comparable with that of the apparatus which they protect, and there may be something to be said for their employment, but the trouble then is that the heat capacities of the cables and other gear forming a circuit differ so widely that the additional complication seems hardly justified. In my opinion it would be much better to provide an electrical thermometer so lagged as to give approximately the temperature of the cable or machine. Such thermometers can be provided with alarm contacts for bells or lamps so as to give the switchboard attendant ample warning that something is wrong.

I am glad that Mr. Stacey has emphasized the importance of differentiating, in the case of an inverse-time-element relay, between the time-lag at a current just greater than that necessary to operate it and that under short-circuit conditions. This is a matter which has not, by any means, received the attention it deserves. Referring to Fig. 6 of the paper, most relays are marked with times corresponding to the points at which the curves cut the vertical through the 100 per cent point. That is to say, the time-lags would be described as 20, 12 and 4 seconds, respectively. But it will be observed that an increase of even 2 or 3 per cent in the current makes a difference of some 50 per cent in the time-lag. In my opinion all relays should be marked with two distinct times: (1) that corresponding to a fault current 20 per cent in excess of the current-setting, and (2) that which the relay will give in the event of a short-circuit. The time-lag at a current which is just sufficient to operate the relay should be known approximately, but is of small importance compared with the others, particularly with the short-circuit time-lag.

To my recommendation that current transformers should be allotted to the protective gear, independently of those required for the measuring instruments (a recommendation endorsed by several speakers), I would add another, namely, that the size of the transformers should not be cut too fine. The volt-ampere consumption of a relay need not be large (15 volt-amperes should suffice in nearly all cases), but too small a current transformer is likely to have a less satisfactory ratio curve at heavy overloads and is, moveover, more difficult to " pair " accurately. One rated at 40 volt-amperes is in my opinion the right size.

Several speakers appear to think that I recommend long time-lags as being desirable in themselves. This is far from being the case ; it is obvious that when once the fault has developed the sooner it is isolated the better for all concerned. But a moderate time-lag forms a most convenient means of discrimination and besides being, in most cases, quite innocuous actually reduces the severity of the short-circuit with which the oil switch has to deal to a fraction of what it would be if cleared instantaneously. In this connection, and in reply to Mr. Clothier, it would be disastrous to *design* an oil switch on the assumption that it will never have to break the full short-circuit current. To take an almost parallel case, the brakes of a tramcar must be so designed as to make an emergency stop possible, but good driving reduces the use of the emergency brake to a minimum.

My contention that " more interruptions of supply are caused by opening the circuit prematurely than by leaving a fault on the system for too long a time " was alluded to by several speakers and was not, I think, controverted by any. At the same time I fully endorse Mr. Porter's desire for further information as to what may and what may not be regarded as safe time-lags under various conditions. In America lags of 8 or more seconds are in satisfactory use, but my own opinion is that 2 seconds should be regarded as a maximum in most cases and as one which may, in certain cases, have to be reduced.

Finally, I fully realize that to many who have been taught to regard " efficient protection " and " special conductors " as wellnigh synonymous expressions it must seem almost heretical to point out how much can be done without these adjuncts, and I can only thank those speakers who were of that persuasion for the broad-minded way in which they have discussed my proposals.

LIVERPOOL SUB-CENTRE: CHAIRMAN'S ADDRESS

By Professor E. W. MARCHANT, D.Sc., Member.

(*Abstract of Address delivered at* LIVERPOOL, 19 *January*, 1920.)

We are now nearing the jubilee of the parent Institution, and it occurred to me to look back in our records and see what the first President of the Institution had to say when it was established in 1872. At that time there were only 110 members, and I may therefore be excused if I repeat some of the wise words that Mr. Siemens uttered on that occasion, because I think they are very appropriate to many of the things we shall have to discuss in connection with the new Sub-Centre that has been formed. His opening sentence, in particular, deserves repetition.

"Our future prosperity will be influenced in a great measure by the direction in which we shall start our pilgrimage. Let us hope, therefore, that our joint efforts may lead us in the direction of true scientific and practical advancement."

He starts by considering whether a Society of Telegraph Engineers, as the Institution then was, was really wanted: "Is Telegraph Engineering not a branch of Civil Engineering, and do not all our proceedings therefore fall within the legitimate sphere of action of the Institution of Civil Engineers ?. . . Is it desirable, indeed, it may be urged, to take a branch from the parent stem and to cultivate it separately ?"

That is a question that the last 48 years has answered with no doubtful and uncertain voice. The Institution has grown in numbers and influence so greatly that it is not very far from the truth to say that nowadays the branch is as great as the original stem. But there is, I venture to think, a still present danger in the question that he asked: "Shall we not degenerate thereby into 'specialists,' or what may be called 'fractional quantities of scientific men,' and this in the face of the patent fact that the further we advance in scientific knowledge (whether pure or applied), the more clearly we perceive the intimate connection between its different branches, and the impossibility of cultivating one without constantly reverting to the others. In answer to such allegations we may fairly assert that we do not intend to become 'specialists' in the narrow sense of wishing to confine the range of our knowledge to the phenomena and appliances which have an immediate application to our professional objects. . . . But our time is limited, and, although the great principles of nature may be understood generally by one person, their applications are infinite.

"If it is impossible for one man to master the special knowledge accumulated in different branches of Engineering Science, it would be equally impossible for one Society to cultivate all those branches in detail."

And so he arrives at the conclusion: "We may, therefore, safely conclude that a Society of Telegraph Engineers is necessary for the more rapid development of a new and important branch of applied science; I further maintain that such an Institution is desirable in order to afford Telegraph Engineers frequent opportunities of meeting each other in friendly intercourse, and of impressing them with the conviction that their united action will be advantageous to the material interests of all.

"The *measure* of usefulness of the new Society must depend, however, in the first place, upon its constitution and upon the amount of support which it is likely to receive, and in the second place upon the well-directed and continued exertions of its members, particularly of those members and associates who have accepted posts of trust in the Council."

All these words seem to me so appropriate to our present position that I make no apology for quoting them, though we are starting the Liverpool Sub-Centre in 1920 with more than twice as many members as the whole Institution possessed at its inception. It seems to me essential that each Sub-Centre should have a character of its own, controlled very largely by local conditions, and I want therefore, in the first place, to stake out our claims and to deal with a few subjects which I think this Sub-Centre is specially well qualified to discuss.

Electric power on ships.—The use of electrical equipment on ships is now becoming increasingly important. Liverpool, of course, is an unrivalled centre for the study of such problems, and it is hoped that, as time goes on, our new Sub-Centre may be able to keep us abreast of the progress that is being made in this direction.

Cables.—We have in this district a very close connection with the cable industry, and the new problems arising in connection with the distribution of electric power from large super-stations will give the members of our Sub-Centre many fruitful evenings of discussion on the design and construction of overhead and cable lines.

Telegraphs.—In Liverpool we have one of the largest factories in the country for the manufacture of telegraph and telephone apparatus. Many Members of Council regret that the discussion of telegraph and telephone problems occupies such a small proportion of the proceedings. I hope that the Liverpool Sub-Centre may help to remedy this. With the enormous growth during the last few years in the use of electrical power for factories and works, it is perhaps inevitable that telegraphy and telephony should take a less prominent place; but at the same time one must recognize that, under present conditions, rapid and efficient means of communication are becoming more and more essential.

Wireless telegraphy.—Of all the branches of this

problem, the one which Liverpool people must most fully appreciate is wireless telegraphy. The shipping industry is by far the biggest in the district, and anything which tends to make the journey of the steamship safer must be of interest to the shipowner.

Electrical engineering in chemical works.—There is another branch of electrical engineering which has hitherto received far too little attention, viz. the engineering problems connected with electro-chemistry. There are, in the neighbourhood of Liverpool, chemical manufacturers who use an immense amount of electrical energy in their processes, and the engineers connected with these undertakings should be able to provide a number of papers and subjects for discussion.

Future of the electrical engineering graduate.—The last few months have seen an enormous influx into our universities and technical colleges. The number taking engineering courses is very large, and the questions may perhaps be asked: What is going to happen three or four years hence, when these men are ready to take their place in industry? Can they be absorbed, or will the supply exceed the demand? Perhaps the best person to answer that would be a man engaged in industry, but I hope it will not be out of place for me to mention one or two salient facts of which we have evidence from countries other than our own, where the number of trained technical graduates has been enormously greater in proportion to population than it has been here.

Personally, I do not feel any doubt that these men, when they are fully trained, will find occupation in electrical engineering. We are on the eve of very big developments, electrical power is being used in every direction for new undertakings, and, even in older ones, where no great gain in economy may be expected as the result of electrification, the great convenience and flexibility of electrical operation have led to its adoption.

One of the most interesting is the practical disuse of the gas engine for generating electrical energy in chemical works. About 15 years ago, one of the largest chemical factories in this district installed a number of gas engines with producer plant for generating the energy that they required. In all the latest additions that are being made, however, steam turbines have been installed with turbo-generators, and rotary converters. For a station with a 100 per cent load factor this is a remarkable change, and it has been brought about in order to avoid the necessity of employing a large amount of unskilled labour.

The most striking phenomenon at present is the unanimous and independent decision that has been reached by the various countries of Europe, notably Holland and Germany, that schemes for a widely extended supply of electrical energy are an absolute necessity.

Training of electrical engineers.—Mr. Peck once said, in a discussion on the education of engineers, that he thought the best thing to specialize in was fundamental principles. I consider this to be one of the wisest things which have ever been said in connection with education. Now, in practical engineering it has to be recognized that the deciding factor in any engineering project is: Will it pay? That is a fundamental principle. If it will not pay, then the capital for carrying it out will not be forthcoming, and, as far as practical results go, the scheme might never have been conceived.

No one is more interested than myself in the scientific side of engineering, but we have got to face the facts. We have got to realize that under modern conditions a vast number of trained engineers are wanted, who shall be equipped, not only with technical knowledge, but with such knowledge also as will enable them to deal readily with commercial problems. If we are to satisfy this need, we shall look to close co-operation with those undertakings and industries which are associated with the works and factories in our district. The outlook for the technical graduate to-day is most encouraging whether he takes up the more scientific side of engineering, namely research work, which is now becoming a standard part of a modern manufacturing establishment; whether he takes up works management, scientific management as the phrase now runs; central station engineering, with the multitude of new problems that will inevitably arise in connection with new super-stations; telegraph or telephone engineering; whether he concerns himself in the electro-chemical problems which are now rapidly coming to the front and are already asking for solution; or whether, as I have suggested, he concerns himself with the commercial problems that require to be dealt with on all sides.

DISCUSSION ON

"FAILURES OF TURBO-GENERATORS AND SUGGESTIONS FOR IMPROVEMENTS."*

North Midland Centre, at Leeds, 9 March, 1920.

Mr. W. M. Selvey: The trend of development in any class of machinery is that after a great change a very rapid advance is always made, and that subsequently the difficulties are met by a process of slow refinement. Eventually these processes of slow refinement result in a design which is found to be a definite limitation to further progress and those who wish to look ahead have to seek some new weapon of attack, some great step forward, which afterwards has to go through the same process of refinement in order to make a satisfactory commercial piece of apparatus. I consider that, although many of us may have thought a good deal about the subject, the author is the first one who has had the courage to come forward and point out the absolute necessity now of considering some great step in advance. It is no criticism of such systems to say at the start that they look unpractical. Everything that is new looks unpractical because there is no experience by which to criticize it, and I think we are indebted to the author for pointing out the impossibility of depending for all time on air cooling. He has boldly put forward the revolutionary proposal that the whole machine shall be one large water jacket, but we are glad to know that Messrs. Parsons have produced a water-cooled rotor. The author goes a long way beyond that. He recognizes that we must tackle the problem of the end turns. The merit of his solution is that in introducing these new appliances he at the same time tries to adopt and improve on any of the old refinements in the way of supporting coils which have been found so necessary in improving the earlier types of machines. In fact he attempts to go a great deal further in supporting coils than has yet been done.

Mr. J. Wright: I can endorse a good deal of the author's remarks, having experienced most of the troubles he mentions. I think, however, one can safely say that the defects he refers to are more or less things of the past and the turbo-alternator of to-day is a great improvement on the machines built 12 years ago. When one considers the new problems which the development of the turbo-alternator entailed, I think every credit is due to designers and manufacturers for the progress that has been made in a comparatively short time. There is still room for improvements, however, and some of the author's suggestions are worthy of consideration. The method of supporting the rotor end-turns is not all that might be desired, and while I do not favour the steel wire or tape direct on the coils I think that a chrome steel cap reinforced with steel wire or bands would be safer. There is one important feature in the design of rotors which is not mentioned in the paper. The slip-rings should not be placed together but one at either end of the rotor. With regard to water cooling, I think that Messrs. Parsons have not had sufficient credit for the development of the water-cooled rotor. It is only necessary to inspect one of these rotors under construction in order to appreciate the sound mechanical and electrical design. Referring to Fig. 13, I do not care much for the author's idea of using the rotor coupling as an outlet for the cooling water. I think he would have great difficulty in making a joint sufficiently tight to prevent water getting into the lubricating system. There is little doubt that the water-cooled stator in one form or another will come sooner or later, and if it is tackled with the same ingenuity as the water-cooled rotor we should have little to fear.

Mr. E. L. Thorp: I should be interested to know whether the author has considered the destructive effect of the steam which might be suddenly generated in the event of a heavy short-circuit producing intense local heat in the neighbourhood of the proposed water-cooled elements.

Mr. J. Shepherd (*in reply*): Mr. Selvey considers the paper broadly and appreciates certain features of novelty which I endeavoured to bring out. The suggested adoption of water cooling is merely a means to an end, viz. a more rigid stator core and better coil supports. In the immediate future turbo-generators will deal with power of a magnitude never previously controlled by mankind. The essential working members, viz. the stator coils, are of necessity mechanically weak in their construction and will require all the support which can be given to them. The continuous winding slot made possible by water cooling gives the maximum coil support possible.

Mr. Wright is undoubtedly correct in stating that improvements in turbo-alternator construction have taken place in recent years. The size of electrical stations and the power developed have of necessity led to the construction of stronger machines. We are now at the commencement of a tenfold increase in the magnitude of the forces to be dealt with, whilst the material to resist these forces is the same mechanically unsatisfactory micanite, or similar insulation. Present methods of construction may or may not withstand the buffeting of such enormous forces; time only will show. If they do not, new methods of construction must be adopted. I quite agree that Messrs. Parsons have not had sufficient credit for their pioneer work in water cooling; their water-cooled rotor is simplicity itself.

Mr. Thorp raises the question of the effect on the water-cooled devices of a heavy short-circuit. To be really dangerous the short-circuit would require to be sustained—a very unlikely condition. Fortunately the latent heat of steam is so high that a dangerous quantity of steam is not likely to be generated at the short-circuit. I take the opportunity of thanking Mr. Thorp for considerable help in the development of the new methods of construction described in the paper.

* Paper by Mr. J. Shepherd (see pages 125 and 265).

BENEVOLENT FUND.

22ND ANNUAL GENERAL MEETING, 20 MAY, 1920

(Held at the Institution of Civil Engineers.)

Mr. ROGER T. SMITH, President, took the chair at 5 p.m.

The minutes of the 21st Annual General Meeting held on 29th May, 1919, were taken as read, and were confirmed and signed.

The Report of the Committee of Management (see below) and the Statement of Accounts for the year 1919 (see page 642) were presented and, on the motion of the President, seconded by Mr. L. B. Atkinson, were unanimously adopted.

It was proposed by the President, seconded by Mr. J. Sayers, and unanimously agreed, that Mr. Sidney Sharp and Mr. J. Attfield, F.C.A., be re-elected Honorary Auditors. On the motion of Mr. L. B. Atkinson, a vote of thanks was passed to the Honorary Auditors for their services during the past year.

The Chairman reported that under Rule 10 the Council had appointed the following Committee of Management for the year 1920–21:

The President (*ex-officio*).

Representing the Council.
- Mr. H. J. Cash
- Mr. H. W. Clothier
- Sir J. Devonshire, K.B.E.
- Mr. D. N. Dunlop
- Mr. J. Sayers
- Colonel H. C. Sparks

Representing the Contributors.
- Mr. W. B. Esson
- Mr. J. H. Rider
- Sir W. Slingo

and the Chairman of each Territorial Centre in the United Kingdom.

The meeting then terminated.

REPORT OF THE COMMITTEE OF MANAGEMENT FOR THE YEAR 1919.

CAPITAL.

The Capital Account stood on the 31st December, 1919, at £5,709 9s. 6d., all of which is invested.

INCOME.

The Statement of Accounts shows that the total receipts during 1919 were as follows:—

	£	s.	d.
Dividends on Investments ..	260	8	8
Interest	6	17	9
196 Annual Subscriptions ..	182	0	0
13 Donations of £5 and over ..	134	0	0
475 Donations under £5 ..	221	7	8
	£804	14	1

The accumulated Income now amounts to £1,750 5s. 8d., of which £1,726 9s. 3d. has been invested.

DONORS AND SUBSCRIBERS.

Lists of the names of subscribers and donors during 1919 have been published in the *Journal*.

Among the larger donations received were two of £26 5s. from Messrs. Babcock & Wilcox, Ltd., and The "Twenty-five" Club respectively, and one of £25 from Messrs. W. T. Henley's Telegraph Works Co., Ltd.

A special appeal for subscriptions to the Fund was made by the Committee at the end of 1919.

The Committee of Management desire to acknowledge their indebtedness to the donors and subscribers, and they venture to urge upon members the pressing need for a generous support of the Fund. Apart from donations the Committee will be grateful for annual subscriptions even of small amounts.

GRANTS.

Twenty-five applications for assistance were received in 1919 and the Committee, after due consideration, made grants in 24 cases. One grant of £30 was made, three of £25, seven of £10, six of £9 15s., one of £9, three of £8 15s., and three of £7 10s., a total of £291 5s. for the year.

WILDE BENEVOLENT FUND.

The Capital Account stood on the 31st December, 1919, at £2,586 19s. 2d., the whole of which is invested and brings in an annual income of £89 12s. 5d.

The balance standing to the credit of the Income Account on the same date was £7 8s. 4d.

No grant was made from this Fund during the year.

THE BENEVOLENT FUND OF THE INSTITUTION OF ELECTRICAL ENGINEERS.

INCOME AND EXPENDITURE ACCOUNT FOR THE YEAR 1919.

Dr. Expenditure.	£ s. d.	Cr. Income.	£ s. d.
To Grants	291 5 0	By Dividends on Investments	200 8 8
„ Printing, Stationery, Bank Charges, and Postage	12 3 2	„ Interest	6 17 9
„ Unexpended Balance carried to Balance Sheet	501 5 11	„ Annual Subscriptions	182 0 0
		„ Donations of £5 and over	134 0 0
		„ Donations under £5	221 7 8
	£804 14 1		£804 14 1

BALANCE SHEET, 31ST DECEMBER, 1919.

Dr. Liabilities.	£ s. d.	£ s. d.	Cr. Assets.	£ s. d.	£ s. d.
To Capital Account :—			By Investments (Capital), at cost :—		
As per last Balance Sheet	5,709 9 6		£901 7s. 7d. Cape of Good Hope 3 % Stock	950 0 0	
„ Income and Expenditure Account :—			£593 1s. 7d. New South Wales 3 % Stock	600 0 0	
As per last Balance Sheet ... £1,248 19 0			£420 Great Eastern Railway 4 % Preference Stock	503 18 3	
Unexpended Balance in 1919 ... 501 5 11			£600 North Staffordshire Railway 3 % Debenture Stock	551 0 9	
	1,750 5 8		£750 East Indian Railway 3½ % Debenture Stock	737 18 9	
„ Sundry Creditors	56 6 2		£300 London and North-Western Railway 4 % Guaranteed Stock	333 11 6	
			£500 New Zealand 3½ % Stock	486 18 6	
			£500 Canada 3½ % Stock	478 16 0	
			£1,126 6s. 3d. 5 % War Stock	1,007 6 0	
				5,709 9 6	
			„ Investments (Income), at cost :—		
			£350 New South Wales 4 % Stock ... £336 18 6		
			£200 3½ % War Stock ... 188 17 3		
			£1,528 8s. 6d. 4 % Funding Loan ... 1,200 13 6		
				1,726 9 3	
			„ Sundry Debtors	3 1 6	
			„ Cash :—		
			At Bankers' ... £27 3 10		
			In hand ... 49 17 9		
				77 1 7	
	£7,516 1 4			£7,516 1 4	

We have audited the above Balance Sheet and Income and Expenditure Account with the Books and Vouchers and certify them to be correct, and have verified the Investments with Certificates from Bankers. The Investments, which are stated at cost, are subject to depreciation.

JAS. ATTFIELD, F.C.A.
SIDNEY SHARP } *Honorary Auditors.*

7th May, 1920.

PROCEEDINGS OF THE INSTITUTION.

647TH ORDINARY MEETING, 25 MARCH, 1920.

(Held at the Institution of Civil Engineers.)

Mr. ROGER T. SMITH, President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting of the 18th March, 1920, were taken as read, and were confirmed and signed.

A list of candidates for election and transfer approved by the Council for ballot was taken as read, and was ordered to be suspended in the Hall.

A paper by Mr. L. Milne, Member, entitled "The Electrical Equipment of Artisan Dwellings" (see page 464), was read and discussed together with the Report on "Earthing" (see page 468) of the Earthing Sub-Committee of the Wiring Rules Committee, and the meeting adjourned at 7.45 p.m.

648TH ORDINARY MEETING, 15 APRIL, 1920.

(Held at the Institution of Civil Engineers.)

Mr. ROGER T. SMITH, President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting of the 25th March, 1920, were taken as read, and were confirmed and signed.

Messrs. H. Brazil and R. W. Hughman were appointed scrutineers of the ballot for the election and transfer of members and, at the end of the meeting, the result of the ballot was declared as follows:—

ELECTIONS.

As Members.

Bristow, Whiston Alfred.
Ogilvie, Alexander, O.B.E., B.Sc.

As Associate Members.

Allen, Ernest Edward.
Baddeley, Douglas Stephenson.
Borthwick, Alexander Charles.
Brand, William.
Bridcut, Lieut.-Col. Sidney Haines.
Broberg, Raymond Victor.
Bromley, Joseph Alfred.
Bull, Walter.
Burgess, Alfred Francis, B.Sc. (Eng.).
Campbell, Arthur Edwin.
Crompton, Frank.
Cunningham, Edward.
Cuss, Arthur Tremlett.
Dandeker, Parasharam.
Dobson, James.
Edwards, Edward.
Essex, George William.
Evans, William Edward.
Fletcher, Cyril Cooper.
Fletcher, George Kenneth.
Fraser, Harold Gordon, M.C.
Fraser, Herbert Cecil.
Freer, Robert McDonald.
French, Bertie.
Gardiner, Frederick Henry.
Gibson, John Maughan.
Glover, Edgar Arthur.
Hanks, William Henry P.
Hannah, Walter William.
Herink, Henry James.
Hollis, Lewis Warburton.
Horley, Robert Eustace G.
Hurst, Alfred John.
King, Cyril Douglas.
King, Mansfield Tagert.
Lawrence, Hugh Wilberforce.
Lawton, James Holden.
L'Estrange, Frederick Robert.
Lloyd, Peter Gleave.
Logan, William Archibald.
Lowndes, Percy Norman.
McDonald, John.
Marshall, James Macouat.
Melton, George Barratclough.
Merriman, Ernest.
Mitchell, William Guy P.
Morgan, George.
Partridge, Thomas Teil.
Patterson, James Boyd.
Philip, Peter.
Pooles, Frank Harry.
Proud, Harry Melville.
Rigden, Sydney Paul.
Ross, William.
Sayer, Cyril Eustace, B.Sc. (Eng.).
Shirshov, Ivan.
Smith, Herbert Horton.
Stanley, George John.
Steveni, Edward John.
Taylor, George Edward.
Taylor, Walter Gilby.
Thackrah, Harry.
Thomsen, Rudolph.
Wallace, Malcolm Gilbert, B.Sc. (Eng.).
Walton, Fred.
Wei, Wing Hon, B.Sc. (Eng.).
Whitgift, Mark.
Wood, Frank.
Woodfull, Balfour.
Yarwood, George Arthur.
Yorke, John Paley.

As Graduates.

Brenegan, Stanley.
Buckley, John Stanley.
Buckley, Joseph Duckworth.
Churchill, Percy.
Hallam, Albert William F.
Hook, Reginald Vincent.
Jaques, Archibald Valentine.
Lamden, Henry James.
Lang, Frank James C.
Longmuir, John Bogie.
McManus, John.
Macnamara, Francis John.
Meecham, Jeffrey.
Ockenden, Francis Edmund.
Ogg, William.
Paterson, David.
Rodrigues, Joseph.
Rose, Francis Joseph P.
Royal, James William.
Satchell, Reginald William.
Scott, Robert Claude.
Smee, Alfred Thomas.
Smith, Ernest Forsyth.
Swain, Vivian Ernest T.
Swale, William Eric.
Tucker, Frederick John.
Turner, Norman.
Turner-Smith, Bernard Westcott.
Uscinski, Alexander.
Ward, Thomas Moore E.
Williams, Bertram Evan.
Willson, Charles Schummelketel, B.Sc. (Eng.).
Wilson, Herbert Walter.

As Students.

Allkins, Arthur Warrington.
Armitstead, James Henry.
Ashmore, Joseph.
Barnes, Wilfred Charles.
Birchall, Laurence Edwin.
Bird, David Grieves.
Brown, Donald Fullarton.
Clark, William Henry V.
Cooper, George.
Copp, Philip.
Deacon, Edward Charles.
Dent, Eric Dixon.
Farrow, Reginald Henry M.
Foulkes-Roberts, David Swynford.
Gildert, Robert.
Gillett, James Keith.
Gorrie, William Campbell.
Gough, Howard Butler.
Hancock, Frederick John.
Harris, Valentine Arthur.
Holman, Horace.
Hullah, Roland Gilbert.
Imrie-Smith, William.
Inward, Thomas William.
Jones, William Gwynn.
Kirkup, Ralph Hugh.
Lewis, Gwilym.
Long, Herbert Howard.
Maffey, Walter John.
Maguire, Austin Joseph (B.Eng.).
Meaby, Francis Charles.
Menesse, Arthur Douglas.
Meyer, Edward Herman.
Palmer, Ronald Frank.
Parikh, Ramanlal Girdhartal.
Parker, Leonard Eustace.
Phillips, Arthur Guest.
Pound, Edwin Thomas.
Price, Arthur John.
Price, Samuel Carrick.
Rhodes, Arnold.
Richardson, Stanley.
Ridley, Allison.
Robertson, Miss Bessie Wolfe.
Russell, John.
Saggerson, Edward Walter.
Samples, Walter.
Searson, Victor Frederick.
Shephard, Alger George.
Sherlock, John Richard.
Smith, Edward Seymour.
Steele, Robert Mansel.

As Students—continued.

Thomas, Joseph.
Thornton, Edward Charles B.
Waring, John.
Watson, Alexander.
Westell, Edgar Philip L.
Winfield, Frederick C. (B.Eng.).

As Associates.

Barrett, Harry George.
Faning, Vyvyan Eaton.

TRANSFERS.

From Associate Member to Member.

Buyers, Charles Stuart.
Christianson, William Alexander.
Wilson, William Hamilton

From Graduate to Associate Member.

Adams, Herbert.
Baker, Charles Ernest.
Critcher, William Thomas.
Richardson, Thomas Carr

From Student to Associate Member.

Bruce, Arthur Stanley.
Couch, William Charles M.
Gibson, Harold Cracroft.
O'Donovan, Daniel Edward.
Wadeson, Maurice.

From Associate to Associate Member.

Dixon, George.

Dr. C. V. Drysdale, O.B.E., Member, then delivered the Eleventh Kelvin Lecture, entitled "Modern Marine Problems in War and Peace" (see page 572). A vote of thanks to the lecturer, proposed by Mr. C. H. Merz and seconded by Dr. W. H. Eccles, was carried with acclamation, and the meeting adjourned at 7.40 p.m.

649TH ORDINARY MEETING, 29 APRIL, 1920.

(Held at the Institution of Civil Engineers.)

Mr. ROGER T. SMITH, President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting of the 15th April, 1920, were taken as read, and were confirmed and signed.

Mr. E. B. O. Hawes, Professor J. T. MacGregor-Morris, and Mr. W. E. Warrilow were appointed scrutineers of the ballot for the election of new Members of Council.

The following donations were announced as having been received and the thanks of the meeting were accorded to the donors :—

Building Fund.—Professor A. Hay.

Library.—The Astronomer Royal, The British Electrical and Allied Manufacturers' Association, Messrs. Butterworth & Co., Messrs. Cassell & Co., Ltd., The Commissioner of Conservation (Canada), Messrs. Constable & Co., Ltd., The Imperial Mineral Research Bureau, Liverpool Corporation Tramways (General Manager), The Meteorological Office (London), R. E. Neale, Nouvelle Société Helvétique, E. Raymond-Barker, R. Rymer-Jones, Messrs. E. & F. N. Spon, Ltd., The Surveyor General of India, The Syndics of the Cambridge University Press, The Technical Publishing Co., Ltd., Mrs. S. P. Thompson, University of Illinois, The Wireless Press, Ltd.

Benevolent Fund.—See Institution Notes, No. 21, page 23, May, 1920.

A paper by Mr. A. E. McColl, Associate Member, entitled "Automatic Protective Devices for Alternating-Current Systems" (see page 525), was read and discussed and the meeting adjourned at 7.45 p.m.

THE JOURNAL OF
The Institution of Electrical Engineers

Vol. 58. AUGUST, 1920. No. 294.

THE ANALYTICAL DETERMINATION OF THE STEPS IN THE STARTER OF A SERIES MOTOR.*

By Stanley Parker Smith, D.Sc., Member.

(*Paper first received* 8 *April, and in final form,* 12 *May,* 1920.)

Summary.

In this paper a simple analytical method for calculating the resistance steps in the starter of a series motor is given, and examples are worked out illustrating the application of the method to the series motor and to two series motors arranged for series-parallel control. The solution of the problem entails a knowledge of the magnetization curve, or of the speed curve, of the motor; but no graphical construction is necessary for obtaining the results. The sets of curves in Figs. 3 and 5 are added to illustrate the results.

1. Introductory.

When metallic starters are used, it is usual to arrange the resistance steps so that the current varies between given limits. Practically all the methods for determining the steps in the starters of series motors are graphical, and the object of the present paper is to describe a simple method whereby a given number of steps can be obtained analytically with the same accuracy and practically with the same ease as for a shunt motor. By using an analytical method, not only is a correct solution obtained without trial and error, but the construction of a diagram is avoided.

The fact that, for definite upper and lower current limits, the steps in the starter of a series motor form a geometric series, is well known (e.g. see "Hilfsbuch der Elektrotechnik," 8th edition, p. 326—article by H. Görges), and some time ago Professor T. Mather drew the author's attention to the analytical expressions for the several resistances in such a starter. These facts are included in the following method together with the further conditions which are necessary for its application to the series motor, and to the series-parallel connection of two series motors.

The examples given in the paper were worked out by students taking the course in Electric Traction at the City and Guilds (Engineering) College, and the author is particularly indebted to Mr. A. C. Beer, Wh.Sch., for his invaluable assistance in preparing the material and the diagrams.

2. Theory.

From the equation for the electromotive force induced in a direct-current machine we can write for the speed

$$N = k\frac{E}{\Phi} \text{ revs. per min.} \quad . \quad . \quad . \quad . \quad (1)$$

where k is a constant for any given motor, and Φ = useful flux per pole.

Now the electromotive force induced in the motor is

$$E = V - RI \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where V = pressure at the supply terminals,
R = total resistance in armature circuit between supply terminals,
I = current in the field and armature of the motor.

Hence Eqn. (1) may be written

$$N = k\frac{V - RI}{\Phi} \quad . \quad . \quad . \quad . \quad . \quad (3)$$

The supply pressure V is assumed to be constant, whilst the current I at starting is kept within the requisite limits by varying the resistance R; also, with series-parallel control, by varying the pressure applied to each motor.

* The Papers Committee invite written communications with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

In order to calculate the resistance steps in a metallic starter, we proceed as follows:

Let I_1 = upper limit of current during starting,
I_2 = lower limit of current during starting,
Φ_1 = flux corresponding to I_1,
Φ_2 = flux corresponding to I_2.

The fluxes Φ_1 and Φ_2 are obtained from the magnetization curve of the motor (cf. Figs. 2 and 4), or, alternatively, from the speed curve of the motor. The use of the flux characteristic in the calculation of the starter arises from the fact that in the series motor the flux is a function of the armature current; whereas, in a shunt motor, the flux is constant, so that the magnetization curve is not needed.

Further, let

$$\left.\begin{aligned} \lambda &= \frac{I_1}{I_2} \\ \beta &= \frac{\Phi_1}{\Phi_2} \\ \alpha &= \frac{\beta}{\lambda} \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

In general, λ and β are > 1, and α is < 1. (In a shunt motor, $\beta = 1$, and therefore $\alpha = 1/\lambda$.)

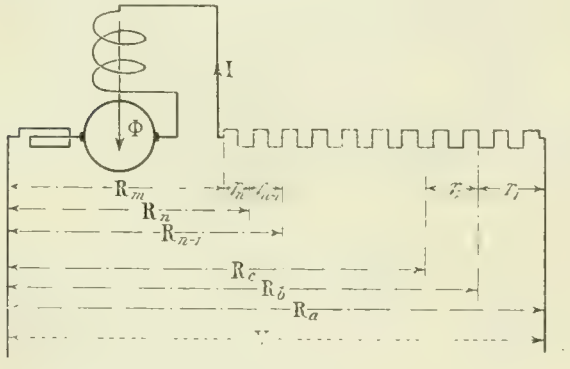


FIG. 1.—Diagrammatic arrangement of starting resistance for series motor.

The conditions during starting are represented in Fig. 1, where R_m = resistance between terminals of motor; R_a, R_b, . . . R_n and R_m = resistances between supply terminals during starting; r_1, r_2, . . . r_n = resistance steps.

Then

$$\left.\begin{aligned} R_a - R_b &= r_1 \\ R_b - R_c &= r_2 \\ &\cdots \\ R_{n-1} - R_n &= r_{n-1} \\ R_n - R_m &= r_n \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad (5)$$

and, in general, $R_{x-1} - R_x = r_{x-1}$

Consider now the instant when R_{x-1} is in circuit and the current has fallen to the lower limit I_2; the induced E.M.F. will then be [cf. Eqns. (1) and (2)]

$$E' = V - R_{x-1} I_2 = N \Phi_2 k$$

At this instant, the resistance step r_{x-1} will be cut out; the current will immediately rise to the upper limit I_1, thereby increasing the induced E.M.F. to

$$E'' = V - R_x I_1 = N \Phi_1 k$$

the speed N not having changed during this transition.

Therefore

$$\frac{E''}{E'} = \frac{V - R_x I_1}{V - R_{x-1} I_2} = \frac{\Phi_1}{\Phi_2} = \beta \quad . \quad . \quad . \quad (6)$$

whence

$$R_x = \alpha R_{x-1} - \frac{V}{I_1}(\beta - 1) \quad . \quad . \quad . \quad (7)$$

This, then, is the general expression for the total resistances in the starter for a series motor. The corresponding expression for the resistances in the starter for a shunt motor (where $\Phi_1 = \Phi_2$, i.e. $\beta = 1$) is $R_x = \alpha R_{x-1}$; in other words, the total resistances for a shunt motor form a geometric series. With the series motor, however, the constant term $(\beta - 1) V/I_1$ has to be deducted from αR_{x-1} in each case.

Coming to the resistance steps, however, a geometrical progression is met with in the starter for the series motor as well as for the shunt motor. This is seen from Eqns. (5) and (7),

for

$$\begin{aligned} r_x &= R_x - R_{x+1} \\ &= \alpha (R_{x-1} - R_x) \\ &= \alpha r_{x-1} \end{aligned}$$

Hence

$$\frac{r_x}{r_{x-1}} = \alpha \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

That is,

$$\begin{aligned} r_2 &= \alpha r_1 \\ r_3 &= \alpha r_2 = \alpha^2 r_1 \\ &\cdots \\ r_n &= \alpha r_{n-1} = \alpha^{n-1} r_1 \end{aligned}$$

In order to find any given step r_x, we have from Eqn. (7)

$$r_x = R_x (1 - \alpha) + \frac{V}{I_1}(\beta - 1) \quad . \quad . \quad . \quad (9)$$

For the first step r_1 this becomes

$$r_1 = R_a (1 - \alpha) + \frac{V}{I_1}(\beta - 1) \quad . \quad . \quad . \quad (10)$$

Now the sum of the n steps [cf. Eqn. (8)] is

$$\begin{aligned} \Sigma_1^n r &= r_1 + r_2 + \ldots + r_n \\ &= r_1 \frac{1 - \alpha^n}{1 - \alpha} \end{aligned}$$

Further,

$$\Sigma_1^n r = R_a - R_m$$

Therefore

$$\Sigma_1^n r = R_a - R_m = r_1 \frac{1 - \alpha^n}{1 - \alpha} \quad . \quad . \quad . \quad (11)$$

Combining this with Eqn. (10) in order to introduce the condition contained in Eqn. (7), developed for the current changes, we have

$$R_a - R_m = \left\{ R_a (1 - \alpha) + \frac{V}{I_1}(\beta - 1) \right\} \frac{1 - \alpha^n}{1 - \alpha} \quad . \quad (12)$$

or,

$$f = \frac{V}{I_1}(\beta - 1) \frac{1 - \alpha^n}{1 - \alpha} + R_m - R_a \alpha^n = 0 \quad . \quad (13)$$

This, then, is the general expression which must be satisfied in order that the n steps give the correct current changes when the switching-in current is I_1. It is seen that a knowledge of the magnetization curve is necessary in order to find the relation between β and α. When this curve is given, together with the number of steps, n, and the motor resistance, R_m, as is usual, Eqn. (13) can be solved by fixing either I_1 or I_2, but not both. (This latter condition also applies to the calculation of a starter for a shunt motor when n and R_m are given.)

Eqn. (13) will now be applied to the calculation of a starter for a series motor, and then modified for the case when the starting current is less than I_1, and for the series-parallel connection of two series-motors.

3. Calculation of Resistance Steps for a Series Motor.

In this section, the case will be considered when the motor starts from rest and the current rises to the upper limit I_1 on switching in. Under these conditions, $R_a = V/I_1$ so that the general expression in Eqn. (12) becomes

$$f = (\beta - \alpha)\frac{1}{1-\alpha} + \frac{I_1}{V} R_m - 1 = 0 \quad . \quad (14)$$

while Eqn. (10) for the first step becomes

$$r_1 = R_a (\beta - \alpha) \quad . \quad . \quad . \quad . \quad . \quad (15)$$

We shall now work out an example, one in which the upper current limit is given; but the same method applies when the lower limit is given.

In case the speed curve (and not the magnetization curve) is given, we have simply to deduce the ideal speed curve, i.e. the speed curve for which $R = 0$, by adding $R_m I$ to the ordinates of the actual speed curve; then since $E = V =$ constant for the ideal speed curve, it follows from Eqn. (1) that the flux is inversely proportional to the speed, whence $\Phi_1/\Phi_2 = N_2/N_1$.

Example 1.—Calculate the resistance steps for a 5-h.p. series crane motor from the following information:—

Applied pressure, $V = 200$ volts,
Upper current limit, $I_1 = 25$ amperes,
Number of steps, $n = 5$,
Resistance of motor, $R_m = 1{\cdot}36$ ohms,
Magnetization curve of motor—see Fig. 2.

Applying Eqn. (14), we get

$$f = (\beta - \alpha)\frac{1}{1-\alpha} - 0{\cdot}83 = 0$$

To solve this expression, we must find a value for I_2 such that $f = 0$. This is quickly done by solving for $I_2 = 18$, 20 and 22 amperes with the values of β found from Fig. 2 and drawing a graph, as shown in the inset in Fig. 2. The following table shows a simple way of arranging the different quantities in the above formula by aid of Fig. 2. In this way we find that $f = 0$ very nearly when $I_2 = 20$ amperes. Further,

I_1 (given)	I_2 (assumed)	$\lambda = I_1/I_2$	Φ_1 from Fig. 2	Φ_2 from Fig. 2	$\beta = \Phi_1/\Phi_2$	$\alpha = \beta/\lambda$	f from Eqn. (14)
			Per cent	Per cent			
25	18	1·39	101·1	90·0	1·123	0·808	+ 0·246
25	20	1·25	101·1	93·5	1·081	0·865	− 0·005
25	22	1·137	101·1	97·0	1·042	0·916	− 0·298

$$R_a = \frac{V}{I_1} = \frac{200}{25} = 8{\cdot}0 \text{ ohms}$$

Applying now Eqns. (15) and (8), the steps, calculated to slide-rule accuracy, are:

$r_1 = R_a(\beta - \alpha) = 8{\cdot}00 \times 0{\cdot}216 = 1{\cdot}73$ ohms
$r_2 = \alpha r_1 = 0{\cdot}865 \times 1{\cdot}73 = 1{\cdot}50$,,
$r_3 = \alpha r_2 = 0{\cdot}865 \times 1{\cdot}50 = 1{\cdot}30$,,
$r_4 = \alpha r_3 = 0{\cdot}865 \times 1{\cdot}30 = 1{\cdot}12$,,
$r_5 = \alpha r_4 = 0{\cdot}865 \times 1{\cdot}12 = 0{\cdot}97$,,
$R_m = 1{\cdot}36$,,

Therefore, $\Sigma_1^5 r + R_m = 7{\cdot}98$ ohms
which is nearly equal to $R_a = 8{\cdot}00$ ohms

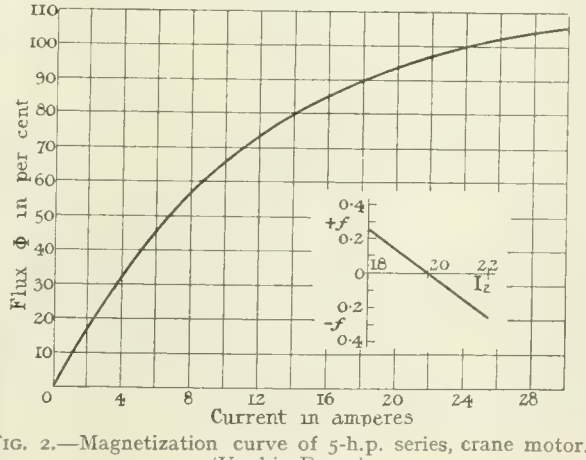


Fig. 2.—Magnetization curve of 5-h.p. series, crane motor. (Used in Ex. 1.)

The slight difference between $(\Sigma_1^n r + R_m)$ and R_a is to be found partly in the solution of the equation for $f = 0$ and partly in the working. It is of no practical importance.

The total resistances are then:

$$\begin{aligned} R_a &= 7{\cdot}98 \text{ ohms} \\ R_b - R_a - r_1 &= 6{\cdot}25 \text{ ,,} \\ R_c - R_b - r_2 &= 4{\cdot}75 \text{ ,,} \\ R_d - R_c - r_3 &= 3{\cdot}45 \text{ ,,} \\ R_e = R_d - r_4 &= 2{\cdot}33 \text{ ,,} \\ R_m = R_e - r_5 &= 1{\cdot}36 \text{ ,,} \end{aligned}$$

For the sake of illustration, the speed curves for these resistances are plotted in Fig. 3. These curves are obtained as follows: To the ordinates of the actual speed curve R_m of the motor are added the values $R_m I$, whence the ideal speed curve is obtained, i.e. the speed curve for zero resistance. The speed curve for any resistance R in circuit is then obtained by deducting the values R I from the ordinates of the ideal speed curve.

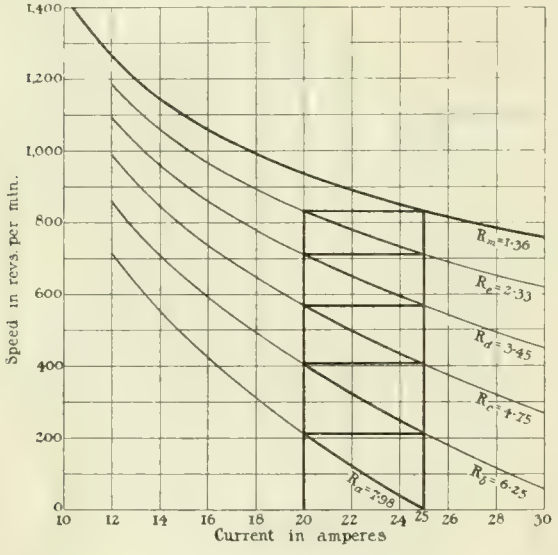


FIG. 3.—Speed curves for 5-step starter for 5-h.p. series, crane motor.

In a similar way, Eqn. (14) can be solved when I_2 is given.

4. Calculation of Resistance Steps for a Series Motor when the Current on Switching in is to be Less than the Upper Limit.

It is sometimes stipulated that the current on switching in shall not rise to the upper limit I_1, but to some value I_3 intermediate between I_1 and I_2.

The total resistance on switching in is then $R_a = V/I_3$, and the first step r_1 is cut out, either automatically or by hand, when the current has fallen to I_2. Let R_a' denote the total resistance when the first step r_1 is cut out, that is

$$r_1 = R_a - R_a'$$

Further, $R_a - R_m = r_1 + r_2 + \ldots + r_n = \sum_1^n r$

and $R_a' - R_m = r_2 + \ldots + r_n = \sum_2^n r$

$$= r_2 \frac{1 - \alpha^{n-1}}{1 - \alpha}$$

Also from Eqn. (9), we have

$$r_2 = R_a'(1 - \alpha) + \frac{V}{I_1}(\beta - 1)$$

Hence the general expression in Eqn. (12) now takes the form

$$R_a' - R_m = \left\{ R_a'(1 - \alpha) + \frac{V}{I_1}(\beta - 1) \right\} \frac{1 - \alpha^{n-1}}{1 - \alpha} \quad (16)$$

We must now express R_a' in terms of R_a. Just before r_1 is cut out $E' = V - R_a I_2$, and just after r_1 is cut out $E'' = V - R_a' I_1$; whence, as in Eqn. (7)

$$R_a' = \alpha R_a - \frac{V}{I_1}(\beta - 1) \quad . \quad . \quad . \quad . \quad (17)$$

Substituting for R_a' in Eqn. (16), the general expression that must be satisfied when the current on switching in is I_3 is obtained, namely

$$f = \frac{V}{I_1}(\beta - 1)\frac{1 - \alpha^n}{1 - \alpha} - R_a \alpha^n + R_m = 0 \quad . \quad (18)$$

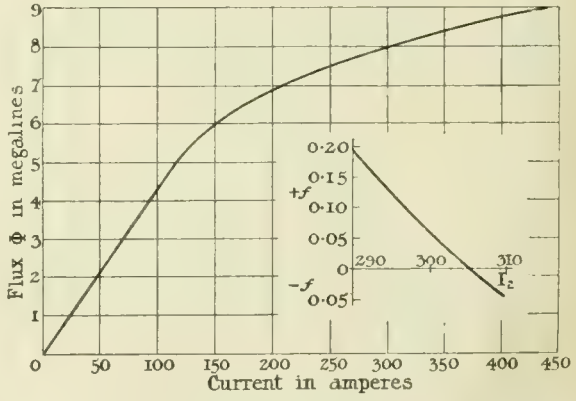


FIG. 4.—Magnetization curve of 250-h.p. traction motor. (Used in Exs. 2 and 3.)

Example 2.—Calculate the resistance steps for a 250-h.p. traction motor, given that

Applied pressure, V = 275 volts,
Upper current limit, I_1 = 400 amperes,
Switching-in current, I_3 = 340 amperes,
Number of steps, n = 4,
Resistance of motor, R_m = 0·1 ohm,
Magnetization curve of motor—see Fig. 4.

We have then

$$R_a = \frac{V}{I_3} = \frac{275}{340} = 0{\cdot}808 \text{ ohm}$$

and

$$\frac{V}{I_1} = \frac{275}{400} = 0{\cdot}687 \text{ ohm}$$

Hence for Eqn. (18) we can write

$$f = 0{\cdot}687(\beta - 1)\frac{1 - \alpha^4}{1 - \alpha} - 0{\cdot}808\,\alpha^4 + 0{\cdot}1 = 0$$

To solve this equation, we assume I_2 = 280, 290 and 300 amperes respectively and find the corresponding

values of β and α from Fig. 4. By plotting a graph, not shown, it is found that $f = 0$ when $I_2 = 286$ amperes.

For $I_1 = 400$ and $I_2 = 286$, we get $\lambda = 1{\cdot}397$, $\beta = 1{\cdot}111$ and $\alpha = 0{\cdot}794$. Hence from Eqn. (17)

$$R'_a = 0{\cdot}565 \text{ ohm}$$

and $r_1 = R_a - R'_a = 0{\cdot}808 - 0{\cdot}565 = 0{\cdot}243$ ohm.

The step r_2 can now be obtained thus,

$$r_2 = R'_a(1 - \alpha) - \frac{V}{I_1}\left(\frac{\beta}{2} - 1\right)$$
$$= 0{\cdot}192 \text{ ohm}$$

The steps in the starter are then

$$\begin{aligned} r_1 &= 0{\cdot}243 \text{ ohm} \\ r_2 &= 0{\cdot}192 \quad ,, \\ r_3 = \alpha r_2 &= 0{\cdot}152 \quad ,, \\ r_4 = \alpha r_3 &= 0{\cdot}121 \quad ,, \\ R_m &= 0{\cdot}100 \quad ,, \end{aligned}$$

Hence $\Sigma_1^4 r + R_m = 0{\cdot}808$ ohm

This agrees with $R_a = 0{\cdot}808$ ohm.

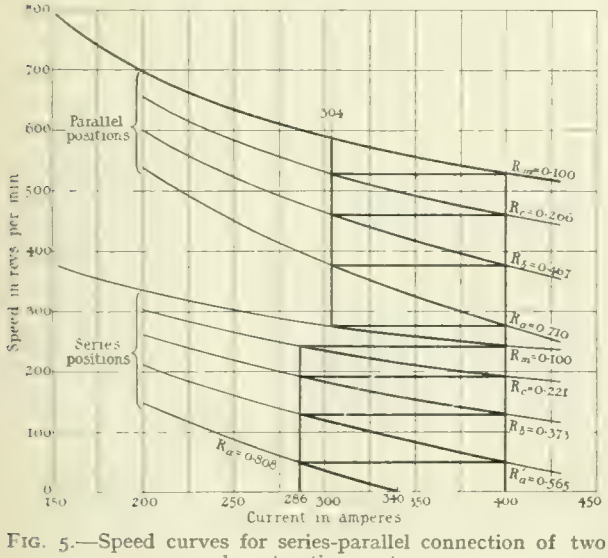


FIG. 5.—Speed curves for series-parallel connection of two 250-h.p. traction motors.

Series steps derived in Ex. 2.
Parallel steps derived in Ex. 3, part (*b*).

The total resistances are therefore

$$\begin{aligned} R_a &= 0{\cdot}808 \text{ ohm} \\ R'_a &= R_a - r_1 = 0{\cdot}565 \quad ,, \\ R_b &= R'_a - r_2 = 0{\cdot}373 \quad ,, \\ R_c &= R_b - r_3 = 0{\cdot}221 \quad ,, \\ R_m &= R_c - r_4 = 0{\cdot}100 \quad ,, \end{aligned}$$

This example, together with the parallel steps in part (*b*) of Ex. 3 for this motor, has been chosen for illustration in Fig. 5. It will be seen that the case dealt with in Ex. 2 corresponds with the series position in series-parallel control.

NOTE.—The values of R in the diagram are for each motor.

5. CALCULATION OF RESISTANCE STEPS FOR TWO SERIES MOTORS WITH SERIES-PARALLEL CONTROL.

This is the case commonly met with in direct-current traction.

For the steps with the series connection, we proceed as in Exs. 1 and 2.

For the parallel positions, the conditions before and after changing-over must be taken into account (cf. Fig. 6).

Let I_1 and I_2 again denote the current limits in the parallel positions. *It must be clearly understood that these limits are not the same as in the series positions.* It is possible to have either I_1 or I_2 the same in both positions, but it will be quite accidental if the two limits are the same in the parallel as in the series positions.

Before paralleling, let the current fall to the value corresponding to I_2 in the parallel positions, then from Fig. 6 it is seen that

$$V - 2E' - 2R_m I_2 = 0$$

After paralleling, let current rise to upper limit I_1, then

$$V - E'' - R_a I_1 = 0$$

Since the speed has not altered during the transition, we have [cf. Eqn. (7)]

$$R_a = \frac{V}{I_1}\left(1 - \frac{\beta}{2}\right) + \alpha R_m \quad . \quad . \quad . \quad (19)$$

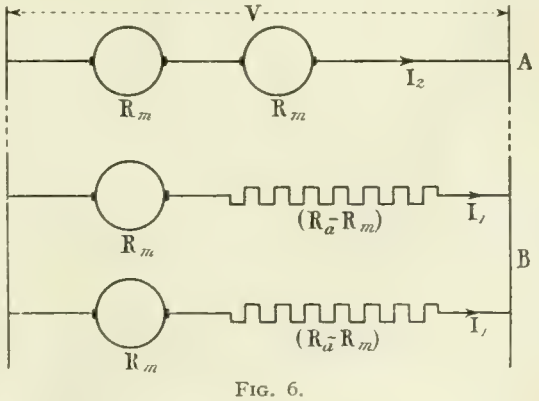


FIG. 6.

A. Connection *before* paralleling.
B. Connection *after* paralleling.

Thus in addition to Eqn. (12), Eqn. (19) must be satisfied in the parallel position. Equating then (12) and (19), we get

$$f = \frac{V}{I_1}\left\{\frac{1 - \alpha^n}{1 - \alpha} \cdot \frac{\beta}{\alpha^n} - \left(\frac{\beta}{2} - 1\right)\right\} + R_m\left(\frac{1}{\alpha^n} - \alpha\right) = 0 \quad . \quad (20)$$

We shall now work out an example of series-parallel control, in which the upper current limit I_1 is chosen the same for both conditions. In the case when the lower limit I_2 is to be the same for both conditions (automatic control with minimum current relay), the problem is solved in a similar way.

Example 3.—Calculate the resistance steps for the series-parallel control of two 250-h.p. traction motors, the particulars of which are set forth in Ex. 2. Given that

Line voltage, $V = 550$ volts,
Maximum current for both series and parallel positions, $I_1 = 400$ amperes,
Number of steps in series connection, $n = 4$,
Number of steps in parallel connection, $n = 3$.

(*a*) *Series positions.*—The four steps in this connection are found in precisely the same way as the steps in Ex. 1; except that Eqn. (14) is solved for $V = 550$ and motor resistance $= 2\ R_m$, i.e. for 2 motors in series.

The results only need be given here. Thus

$I_1 = 400$ amperes,
$I_2 = 297$,,
$r_1 = 0{\cdot}389$ ohm
$r_2 = 0{\cdot}317$,,
$r_3 = 0{\cdot}258$,,
$r_4 = 0{\cdot}210$,,
$2\ R_m = 0{\cdot}200$,,

Whence $\Sigma_1^4 r + 2\ R_m = 1{\cdot}374$ ohm
whilst $R_a = 1{\cdot}375$,,

(*b*) *Parallel positions.*—For the parallel steps, we have by substituting $I_1 = 400$, $V = 550$, $R_m = 0{\cdot}1$ and $n = 3$ in Eqn. (20)

$$f = 1{\cdot}375 \left\{ \frac{1 - a^3}{1 - a} \cdot \frac{\beta - 1}{a^3} + \frac{\beta}{2} - 1 \right\} + 0{\cdot}1 \left(\frac{1}{a^3} - a \right) = 0$$

To find the value of I_2 for which $f = 0$, we assume $I_2 = 290$, 300 and 310 amperes, and find the corresponding values of λ, β and a by aid of the magnetization curve in Fig. 4. These are set forth in the following table. From the graph in the inset in Fig. 4 we then find that $f = 0$ when $I_2 = 304$ amperes.

From Eqn. (19) we then get

$$R_a = 0{\cdot}709 \text{ ohm}$$

and, from Eqn. (10) or (11),

$$r_1 = 0{\cdot}243 \text{ ohm}$$

The steps in the parallel positions are then

$r_1 = 0{\cdot}243$ ohm $r_3 = 0{\cdot}166$ ohm
$r_2 = 0{\cdot}201$,, $R_m = 0{\cdot}100$,,

Thus $\Sigma_1^3 r + R_m = 0{\cdot}710$ ohm,
which is nearly equal to $R_a = 0{\cdot}709$ ohm.

The total resistances for each motor are then

R_a . . $= 0{\cdot}710$ ohm $R_c = R_b - r_2 = 0{\cdot}266$ ohm
$R_b = R_a - r_1 = 0{\cdot}467$,, $R_m = R_c - r_3 = 0{\cdot}100$,,

The speed curves for these three steps in the parallel positions are shown in Fig. 5.

It is thus seen that with a maximum current of 400 amperes the limits are

Parallel positions: 400 and 304 amperes.
Series positions: 400 and 297 amperes.

If, however, the current on switching in is to be less than I_1, for example 340 amperes, then, as shown in Ex. 2, the limits in the series positions are 400 and 286 amperes. Obviously such a restriction of the current on switching in has no influence whatever on the limits in the parallel positions. It must be borne in mind that in the series positions there are two motors in series, and the resistances have been calculated accordingly in Ex. 3. If each motor is to have a separate resistance, the calculated values must be halved. In the case of the parallel connection the calculated values are for each motor; hence, if a common resistance be used, the values of the resistances must be halved in order to produce the same pressure drop. In each case, the capacity of the resistance must be adjusted accordingly.

I_1 (given)	I_2 (assumed)	$\lambda = I_1 / I_2$	Φ_1 from Fig. 4	Φ_2 from Fig. 4	$\beta = \Phi_1 / \Phi_2$	$a = \beta / \lambda$	f from Eqn. (20)
400	290	1·379	8·76	7·92	1·106	0·802	+0·189
400	300	1·333	8·76	8·00	1·095	0·821	+0·066
400	310	1·291	8·76	8·08	1·084	0·839	−0·047

SOME RECENT DEVELOPMENTS OF HIGH-CURRENT ARCS, WITH SPECIAL REFERENCE TO SEARCHLIGHTS.*

By J. Paley Yorke, Associate Member.

(*Paper first received* 6 *January, and in final form* 11 *May*, 1920.)

Preface.—The paper deals principally with the developments which have been made in high-current arcs between plain carbons during the war period, and with a method of comparing the relative intensities of searchlight beams at working ranges.

The main development of the high-current arc has been in the direction of increasing the current density through the carbons and across the arc gap. It has already been shown in a paper read recently before the Institution † that an increase in the current density produces an increase in the total candle-power for a given current, and this was a verification of the author's work in the development of army searchlights. It is here shown how it is possible to run plain carbons at a current density up to 0·31 ampere per square millimetre of the area of cross-section of the positive carbons smoothly and silently by acting upon the arc stream with an electromagnetic "control."

The effects of impregnating carbons in so far as they apply to searchlights are also described, and the characteristics of the high-current arc are briefly touched upon.

The author regrets that he is unable to publish actual results of beam intensities and total fluxes of light received over the working ranges, and that he can only make comparisons, but the National Physical Laboratory tests should suffice to give confirmation of the basic points that an increased current density in the arc yields an increased flux of light per watt, and that it is possible to run plain carbons at a much higher current density by acting upon the arc stream with the electromagnetic control here described than without it.‡

1. Prior to 1914, searchlights were only used for working in an approximately horizontal direction either for work in the field or for naval operations. When plain electric arcs were used the carbons were arranged horizontally, with a common axis which coincided with the optical axis of the mirror or lens.

An arc formed between two horizontal electrodes naturally arches due to the convection effects of the heated air about it, and produces three evil tendencies: the actual path of the arc stream is greater than the distance between the electrodes; the arc tends to be blown out; and the crater tends to form on the upper portion of the face of the positive carbon with a lip on the lower portion.

The introduction of a soft core through the centre of the positive electrode had the effect of minimizing this latter tendency, inasmuch as the core became the centre of the crater, but there was still a tendency for it to be cupped in an upward direction. The core had the further advantage of steadying the arc stream and preventing it from wandering around the face of the positive electrode.

The next stage in improvement was the introduction of a magnetic deflector the magnetic field of which would act upon that of the arc stream, tending to counteract the upward effect of the convection currents and so straighten the arch. This deflector consisted of a portion of an iron ring surrounding the arc. The magnetic field of the arc current magnetized the ring in such a direction that the flux between its poles exerted a downward force on the arc stream.

Fig. 1 (*a*) is a diagrammatic illustration of the resultant flux about the arc, and represents a cross-section looking towards the negative carbon; (*b*) represents a side view to illustrate the relative positions used in practice.

Whilst this deflector did produce improved operation, one fears that little attention was paid to its design, and the variation of its magnetic properties due to temperature variation—especially at its polar regions—sometimes made the debit side greater than the credit.

2. When the searchlight came to be used for anti-aircraft work the projector had to be elevated and the arc inclined at various angles from 30° to 150° with the horizontal. At each angle of elevation the convection effects of the hot air were vertically upwards, whilst the magnetic effect of the deflector was always at right angles to the axis of the carbons. Thus there could be no balance of effects at any angle of elevation, and the difficulty of maintaining a steady arc and a central square crater was tremendously increased.

It was usually possible to move the positive carbon out of the normal axis by tilting the positive carbon holder which could be swung in two planes. In this way one could burn off any lip which had formed. The great disadvantage of this was that the crater was thrown out of the axis of the mirror and the beam was consequently distorted.

A further proposition was that the carbon should be capable of rotation axially so that malformations could be corrected without turning the crater off the axis of the mirror. Though more complicated mechanically and electrically this is undoubtedly better, but its advantages are somewhat obscured when we get carbons which are not straight. There is also the fact that the arc stream tends to hang on to its crater, and should

* The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

† C. C. Paterson, J. W. T. Walsh, A. K. Taylor, and W. Barnett: "Carbon Arcs for Searchlights," *Journal I.E.E.*, 1920, vol. 58, p. 83.

‡ *Ibid.*, p. 106.

a crater be formed towards the upper face of the carbon, and a protruding lip on the lower, the action of turning the carbon axially through 180° will move the arc stream with it so that we now have the crater below and the lip above, and the correction time will be fairly great.

3. The relationship between the diameter of the carbons and the strength of the current in the arc had, up to this stage, been almost entirely determined by considerations of reasonably steady and quiet burning.

It had been found through experience that a current density of about 0·15 ampere per sq. mm. of the area of the cross-section of the positive carbon represented a relationship between area of carbon and strength of current which gave reasonable smoothness, and that any attempt to increase this, either by increasing the current in a given carbon or decreasing the diameter of the carbon for a given current, produced impracticable arcs. Thus it was the practice to use large diameter carbons — for example, a 38 mm. diameter positive carbon for 120 amperes. (Incidentally it may be stated that this carbon could carry considerably greater current than this without becoming red hot.)

The formation of the crater under these conditions was of the generally accepted type, the end of the positive carbon tapering so that the diameter of the crater cup proper was considerably less than that of the carbon. An end view of such a carbon showed that the brightness per sq. mm. of the whole surface was not uniform.

It would seem to follow from this that if the total heat energy could be concentrated on to a smaller diameter carbon there would be an increase in the average temperature per square millimetre of carbon face exposed, and a consequent increase in the percentage of light emitted per watt of energy expended.

On the other hand, if an increase in current does not increase the temperature at the centre of the crater but simply extends the area of maximum temperature, there will be a limit of improved efficiency when that current has been reached which is just capable of heating the whole of the carbon face to the maximum temperature, and any further increase of current beyond this point would merely tend to heat a greater length or depth of the carbon. Whilst such heating would add to the total flux of light emitted from the positive carbon (from its side), it would not add much to the flux which could be reflected from a searchlight mirror within a given angle of beam dispersion. Moreover, such excessive heating along the carbon would cause rapid spindling.

However, under the conditions of running already stated it was not possible to work at higher current densities than 0·15 ampere per sq. mm.

MM. Blondel and Jean Rey have pointed out that the intrinsic brilliancy decreases with the increase of the current and diameter of carbons, i.e. for a given current density the intrinsic brilliance decreases as the current and therefore the diameter of the carbon increases, and they ascribe the difference as being due to defects in the manufacture of carbons of large diameter.

M. Rey said *: " If it were possible to give a greater stability to large arcs and to obtain more shallow and less irregular craters either by modifying the composition of the core or of the carbon or by some outside physical action, it is certain that, instead of diminishing with the increase in the current density, the intrinsic brilliancy would remain unchanged or would even increase. From this it is apparent that there is opportunity for considerable improvement in the burning of large arcs, which would lead to the more frequent use of large searchlights."

Again, Mrs. Ayrton said †: " In every way possible, therefore, the arc burns most economically when the carbons are the very smallest that can carry the current, without danger of hissing, in the case of the positive, and without burning too fast, in the case of the negative."

4. In order to be able to maintain a perfectly uniform crater at all elevations without moving the carbons at all, except to feed them, the author devised a scheme whereby the arc stream could be acted upon in all directions perpendicular to the axis of the carbons by magnetic forces. The disposition of the forces was such that the arc stream was always being urged towards the centre of the positive carbon in a straight line

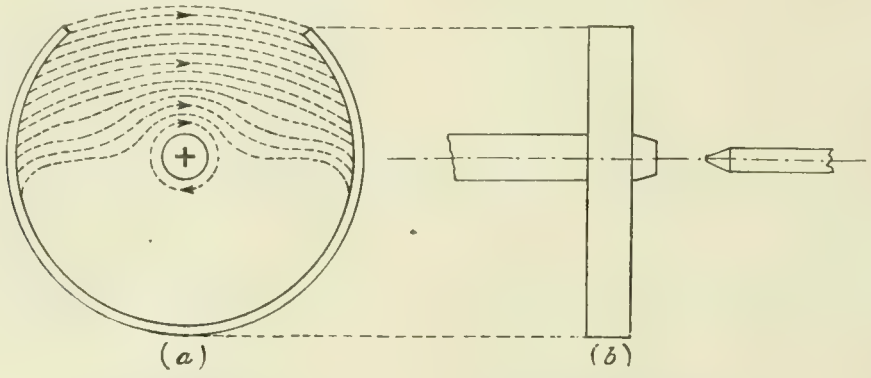


FIG. 1.

* "The Range of Electric Searchlight Projectors," p. 22.
† "The Electric Arc," p. 380.

from negative to positive electrodes. Furthermore, the system of forces was adjustable in space so that any inequality of burning of the positive carbon could be corrected. Inequality of burning seems to be inevitable at the present time owing to the lack of homogeneity in the carbons.

The scheme consisted in an arrangement of four bare copper conductors placed parallel to the axis of the carbons. One of these was vertically above the axis (assuming a horizontal arc for the purpose of description), another vertically below, and the other two were placed one on each side of the axis in the same horizontal plane. They were connected in series with one another and with the arc.

The general arrangement is shown in Fig. 2, and Fig 3 represents the general assembly in a projector the mirror of which has been removed. The conductors are supported from the four bosses M_1, M_2, M_3, M_4, of the metal frame M. Two of these are insulated from the frame, namely at M_1 and M_4. The current is led into the conductors by means of an asbestos-covered flexible coupling at M_1; it passes along the conductor thence up to the top conductor, by the cross-connection at the far end, and so towards M_2, from where it passes along the frame to M_3, then along its conductor and then down to the bottom conductor by the other cross-connection at the far end and towards the insulated boss M_4, from whence it is led by means of a second asbestos-covered flexible conductor.

The framework and conductors are mounted on a platform K which can be raised or lowered or moved horizontally to and fro as shown. The operating rods and wheels are shown in Fig. 3, E_1 and D_1 being universal couplings between the control rods and the mechanism, and E_2 and D_2 being the operating wheels outside the projector. As a matter of fact there have been many improvements in mechanical details since these figures were drawn two years ago, so that they should only be regarded as illustrating the principle.

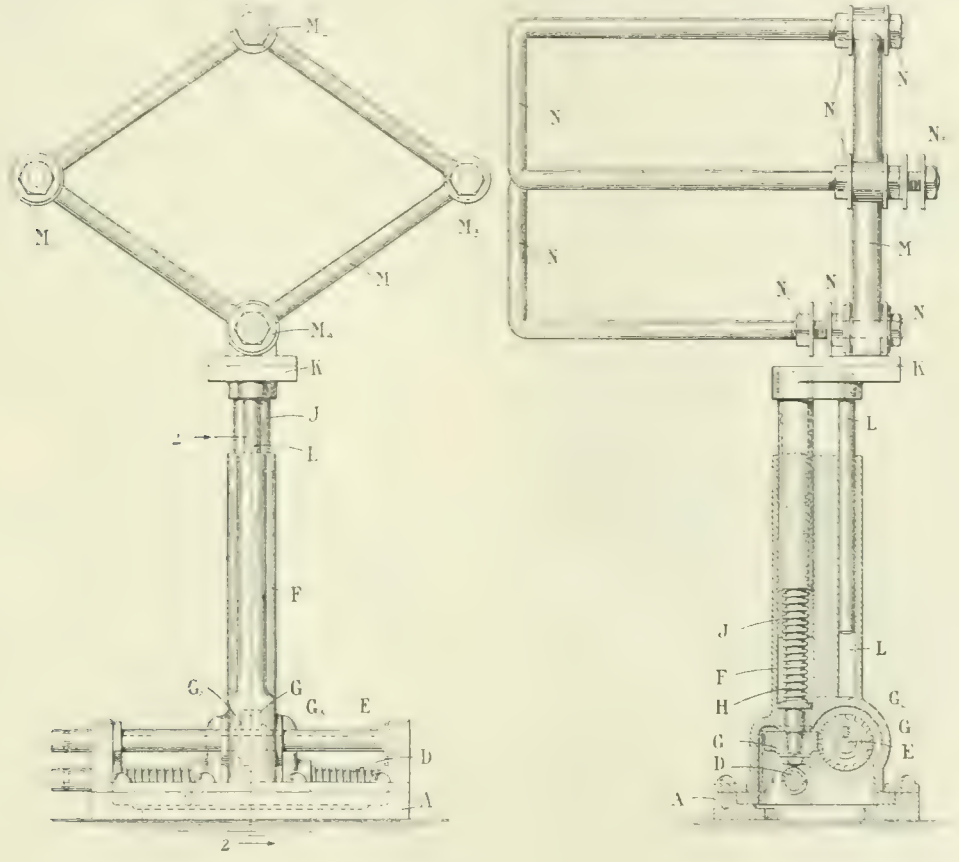


FIG. 2.

Fig. 4 is a diagrammatic representation of the resultant magnetic field about the arc stream. It represents a section across the arc stream looking towards the negative electrode. T and B represent sections through the top and bottom conductors, whilst R and L represent those through the side conductors. The directions of the currents are indicafed conventionally, and directions of the magnetic forces are shown by arrows.

It is seen that about the arc stream we have a magnetic field parallel to and in the same direction as the field produced by the current in the arc, and as there is pressure across a magnetic field it follows that the arc stream is being urged towards the centre of the system.

If the framework carrying the four conductors be moved up or down it will be seen that the upward or downward force upon the arc will be changed. If the system be moved to the left then the pressure will be increased towards the right, and vice versa. In this way any tendency for the crater to burn irregularly can be counteracted.

There is a reason for placing R and L further than T and B from the centre of the arc, for if they be uniformly spaced the system will be found to be unstable. It might also appear that the same or a better effect might have been obtained by spacing the conductors uniformly and passing the currents through all against the direction of the arc current—that is to say, having all the conductors exerting repulsive forces upon the arc The resultant flux about such a system of conductors would, however, tend to encircle them completely, leaving little or no flux inside.

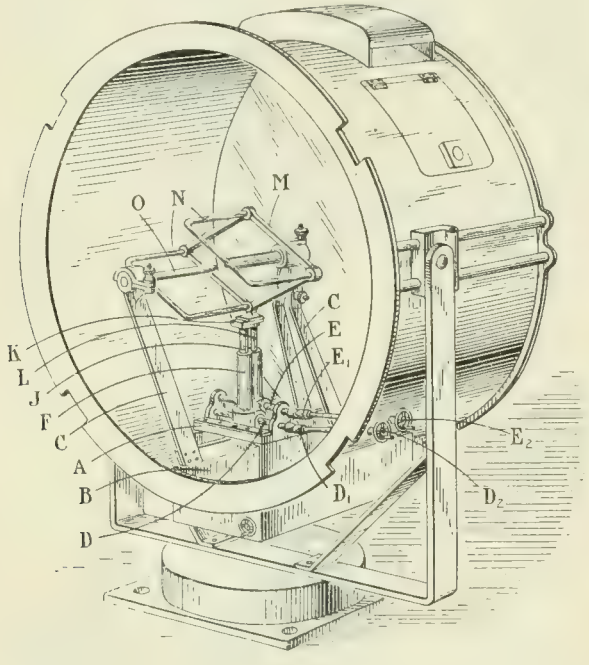


FIG. 3.

5. The effect of the magnetic control upon the crater depends, for a given current, upon the distances of the conductors of the system from the arc and upon the size of the carbons. If the distances be lessened, i.e. if the magnetic controlling forces be increased, the arc stream tends to bore into the positive carbon, and the author has known of craters of 1 inch to 1½ inches depth. Such craters are quite useless (except as excellent miniature electric furnaces), and one may say generally that any kind of cupping effect is sure to bring ultimate trouble owing to the extreme difficulty —almost impossibility—of maintaining that cup with uniformly thick walls. Also, when one edge of the cup burns away there is an unsteady arc until the operator has burnt away the remainder and restored uniformity. It is obvious that the deeper the crater the longer will it take to readjust the arc once the crater wall has broken. Therefore the distances of the control conductors are arranged so that there is no serious boring tendency. Different frames have been designed for different currents, but in general each frame has a fairly wide range of current in which it will operate satisfactorily. For example, the frame designed for a 225-ampere arc will operate arcs at currents from 190 to 260 amperes.

Most of those who saw the controlled arc working for the first time were surprised that the copper conductors and the copper frame carrying the conductors did not melt, especially the top conductor which is generally in the flame and nearer to the arc than any of the others. It was a matter of wonder and even relief to the author. But it is absolutely essential that the conductors be connected on the negative side of the arc so that they are at a lower potential than any part of the arc. If they be on the positive side, then whilst all may run smoothly and quietly for a little time, suddenly a conductor or the frame will melt through. That is to say, we get two arcs in parallel from the common negative, one to the normal positive and the other to the frame, or to one of the conductors, according to the elevation of the lamp at the moment. It is this arcing and not the normal heat of the flame which causes the breakdown.

This has never happened, to the author's knowledge, with the frame on the negative side of the arc, and it is of interest to know that the section of copper conductors used has always been less than would satisfy the "1,000 amperes per square inch" rule. In the author's first experiments the frame was connected on the negative side merely because it was more convenient. Many weeks later on trying out improved designs in a different projector the frame was connected on the positive side, again for convenience. The author's dismay may perhaps be dimly realized when the frame melted in a few minutes. Of course the occasion was a demonstration!

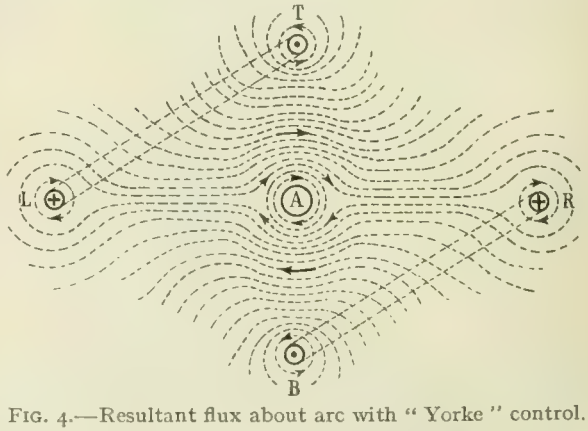


FIG. 4.—Resultant flux about arc with "Yorke" control.

6. It was now considered possible to maintain a steady arc at a given current between carbons of smaller diameter than had hitherto been used (§ 3 above). It was also seen and verified that the soft core of the positive carbon might be abolished with advantage. The presence of the core assists deep crater formation which is not desirable, and furthermore it is always

found to have a lower intrinsic brilliancy than the carbon immediately around it; that is to say, the core produces what is relatively a dark spot at the centre of the crater. When the arc was "controlled" the core burnt away more rapidly than it had done previously, leaving a deep hole which of course was also a dark spot.

Investigations were then carried out with solid positive carbons of different diameters and a controlled arc at a given current. The points to be investigated were smoothness of burning and ease of manipulation, together with the total flux of light produced in a searchlight beam and the intensity of the beam across its diameter.

The method of these tests is described below, but here it may be stated that within the ranges of our initial investigations, viz. 80 amperes to 250 amperes, the best results were obtained when the relationship between the strength of the current and the area of cross-section of the positive carbon was given by the empirical expression $\sqrt{I} = r$, where r is the radius of the positive carbon in millimetres. Thus a current of 225 amperes will yield (according to our investigations) the best result in terms of total flux in a beam of given dispersion, together with smoothness of running and ease of manipulation, when a solid carbon of 15 mm. radius is used.

This is equivalent to saying that the current density is $1/\pi$ amperes per sq. mm. of the area of cross-section of the positive carbon. This is purely empirical and the author does not claim to have discovered any new property of π. Perhaps it would be better to state the current density as 0·31 ampere per sq. mm., i.e. twice as great as the maximum current density which could be used without the control and with plain carbons.

It should be understood that this value of the current density represents the maximum so far attained which could be used with plain carbons whilst still maintaining ease of manipulation and smoothness of running, and that it was necessary, in order to secure this smoothness and steadiness, to control the path of the arc stream.

The actual results of beam intensities and total fluxes of light obtained at a given range with controlled and uncontrolled arcs at different current densities may not be published, but it may be stated that an arc run at 0·31 ampere per sq. mm. will yield 50 per cent more total flux in a searchlight beam than one with the same current but at a current density of 0·11 ampere per sq. mm. (for example, 120 amperes with a 22 mm. positive and 120 amperes with a 38 mm. positive). Furthermore, it was possible to obtain a smaller angle of beam dispersion for the same current, and thus a higher intensity at the centre of the beam.

The authors of the paper on "Carbon Arcs for Searchlights" already referred to give in par. 16 the empirical expression $C = 150\,I - 5\,A - 2{,}000$ for the candle-power C of an arc in terms of the current I and the cross-sectional area A of the positive carbon in sq. mm. If this be applied to the example quoted above, a gain of 40 per cent in the total candle-power C is given by the use of the 22 mm. carbon instead of the 38 mm.

The gain in the beam is higher than this, presumably because the 40 per cent gain in the total candle-power is all in the crater flux, so that there is a greater percentage of the total flux falling upon the mirror in such a direction that it is reflected back within the useful angle of beam dispersion.

7. When these "best results" were obtained it was found that the crater almost filled up the entire face of the positive carbon and burnt with a shallow saucer-like formation with fairly sharp edge. Fig. 5 illustrates a fairly typical pair of formed electrodes, the dotted line indicating the crater depth.

It was found that carbons of greater diameter than 20 mm. when run at this density became hot along their entire length and therefore would spindle rapidly. To overcome this the positives were copper-plated. The problem here was to put on a sufficient thickness of copper to overcome the heating difficulty but not enough to cause serious drippings of molten copper, such drippings being very undesirable in anti-aircraft work owing to their falling upon the mirror at the high elevations of the projector.

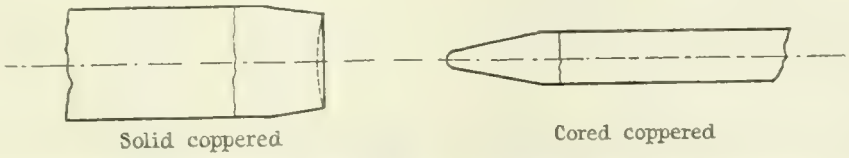


FIG. 5.—Showing relative sizes of carbons for controlled arc and burning length and carbon formation (dotted line indicates crater depth).

Thus, so far as the plain carbon arc was concerned, the author had concluded that the best results were obtained by using a "controlled" arc between a solid copper-coated positive carbon, of such diameter that the current density was 0·31 ampere per sq. mm. of its cross-section, and a cored copper-coated negative carbon of such diameter that the current density in it was about 1 ampere per sq. mm. of its cross-section. And he had further decided that the initial shape of the carbon ends should be flat in the case of the positive and more pointed in the case of the negative than had hitherto been the rule.

As Mrs. Ayrton has often pointed out, the negative electrode is of tremendous importance. A flat-nosed negative is an abomination, magnetic controls, impregnations, or carbon rotations being powerless to produce steady burning. We find that the tendency to produce "mushrooms" on the negative is decidedly diminished by the use of the solid positives instead of the cored.

We have tried Mrs. Ayrton's suggestion of using a hollow negative, but are unable to report favourably upon it at currents of 180 to 250 amperes. We found

that we got spasmodic bursts of gas through this hollow which did not conduce to smooth running.

We have used both solid and cored negatives and the author has no hesitation in preferring the cored negative over any of those so far tried for the high currents referred to—but it is possible that other expedients may be necessary for still higher currents.

The author believes that with an electromagnetic control there need be no limit to the strength of the current which could be used whilst maintaining a steady and quiet arc, but so far there appears to be a limit to current density with plain carbons.

8. Before referring to the characteristics of the controlled arc, or to the question of impregnated carbons, it will be advisable to describe the method used for comparing the searchlight beams produced by the different arcs.

The author always maintained that, in order to decide upon the suitability of an arc for searchlight purposes, it was essential that the arc should be burned in a projector and a measure taken of the total flux of light in the beam at a place no farther from the projector than the average distance at which it was expected to operate. It should also be ascertained what was the minimum angle of dispersion which could be produced by the various arcs under test with a given mirror, and what was the intensity of illumination across the width of the centre of that beam at the place where the observations were being taken.

It is well known that if we place at the focus of a paraboloidal mirror a number of craters of different diameter each being of the same intrinsic brilliancy per square millimetre and *of uniform brilliance over the whole of the surfaces*, then the only effect produced in the resultant beam is to increase its angle of spread, and of course its total flux of light. There will be no change in the intensity of the beam at the centre. It would thus seem that if we had a maximum of crater brilliance we had also reached a maximum of beam intensity *with a given mirror*.

On the other hand, if we place at this focus two craters of different diameters, the larger one being non-uniform in crater brilliance with a maximum crater brilliance at the centre only, whilst the small one is uniformly brilliant with its edges as bright as its centre, and the sizes of these carbons are such that the total flux of light from the small crater is at least equal to that of the larger, then the general intensity of the small crater beam will be higher than that of the large crater beam.

If now the small crater be assumed to have a greater total flux of light than the large crater, the average intensity of its beam will be still higher. Further, if we shift the position of this small crater slightly with respect to the focus so as to obtain a beam of equal divergence to that produced by the large carbon, then the average intensity of its beam will still be greater than that produced by the large carbon.

Thus we expected to get both a greater flux and a greater average beam intensity, in a beam of given divergence, when using a controlled arc at the higher current density.

The searchlight requirements for aircraft work were a beam of high intensity combined with fairly wide dispersion, for it would obviously be difficult to "find" a small target like an aeroplane with a narrow beam, however great its intensity might be.

9. The beam flux and intensity were measured at ranges between 12,000 and 25,000 feet from the projector. The beam was projected to the observing station so that the photometer was at its centre. The candle-feet illumination received upon a screen was measured, and the beam was traversed through $\frac{1}{4}$ degree to the right; the illumination produced was again measured and the beam traversed through another $\frac{1}{4}$ degree and so on until the photometer screen was "outside" the disc of the beam. This was easily seen by the director of operations at the projector station, as a car headlight pointing towards him was placed just in front of the photometer station to show position and we were only concerned with the edge of the "useful" beam which could be seen by the projector director. (We had, as a preliminary, tried traversing the beam until the photometer observer gave the signal "out," and we found on comparing the two methods that the projector director could judge just as well and that such judgment represented working conditions better.) The projector was then swung back to the centre position and readings were taken; it was then traversed by $\frac{1}{4}$-degrees to the left until the edge was reached and then brought back to the centre. This represented one complete traverse, and each beam was traversed thrice in succession for every exposure.

One type of arc and projector was chosen as the standard of reference—a controlled arc between plain solid carbons of certain diameters run at a certain arc length, current and voltage, and kept always at a certain distance from the mirror.

To ensure all this, one operator was made responsible for the uniformity of the crater, another for the arc length and the position of the crater, whilst a third attended to the current and pressure.

To facilitate the keeping of a constant arc length and position of the crater we arranged a focuscope on the projector so that a full-sized image of the arc was thrown upon a graduated translucent screen.

Having made three traverses (i.e. one observation) with the standard beam we followed it up immediately with an observation of the beam under comparison. This was in turn followed up by a repeat of the standard, and so on. If on repeat with the standard there were discrepancies, they were due either to atmospheric changes or to variations in the arc.

10. As a check on atmospheric changes we attempted the measurement of a "transmission coefficient" each night and at frequent intervals during each night.

The principle of this was as follows: A large white screen was erected at S in Fig. 6 which represents a plan of the test station. The photometer station P was on the top of a ridge of hills and the projector station was on the top of a lower hill. This screen was uniformly illuminated by a framework of incandescent lamps shielded so as not to throw any direct light towards the projector station, where we had a telescopic photometer T by means of which we could measure the illumination of the screen as seen through the atmosphere. At the same time the actual illumination of the screen

was measured close to it, and the ratio of the apparent candle-feet of the screen to the real candle-feet was taken to represent a coefficient of transmission of the atmosphere through the given distance. It was felt that, though this might not be true for the different qualities of the various arcs used, it would at least serve the very useful purpose of showing us whether the atmospheric conditions with regard to light transmission were changing or not during our tests on any night. And, indeed, for that purpose it was invaluable, for all results taken over a period during which the atmospheric conditions varied were discarded when we came to compare the various beams.

As a matter of fact we were not able to make use of our transmission coefficient as an equalizing factor between the results of any one arc taken on different nights, but as stated above it was a valuable " pointer."

means of a Holophane lumeter at the distant station simultaneously.

Our photometric standards of reference were all run at constant current so that ammeters and variable rheostats were used. It was realized that we could not expect very high degrees of accuracy, but we took all possible steps towards making for consistency wherever it was possible.

It must also be borne in mind that errors of plus and minus 5 per cent were not in themselves very serious from our point of view, for if various lights tested only differed by such an amount we should not be justified in either accepting or rejecting them on that account. Other factors would then be the determinants.

The frame of lamps which illuminated the distant screen was also run at constant current. This screen was of canvas painted with white lead, and the lamps

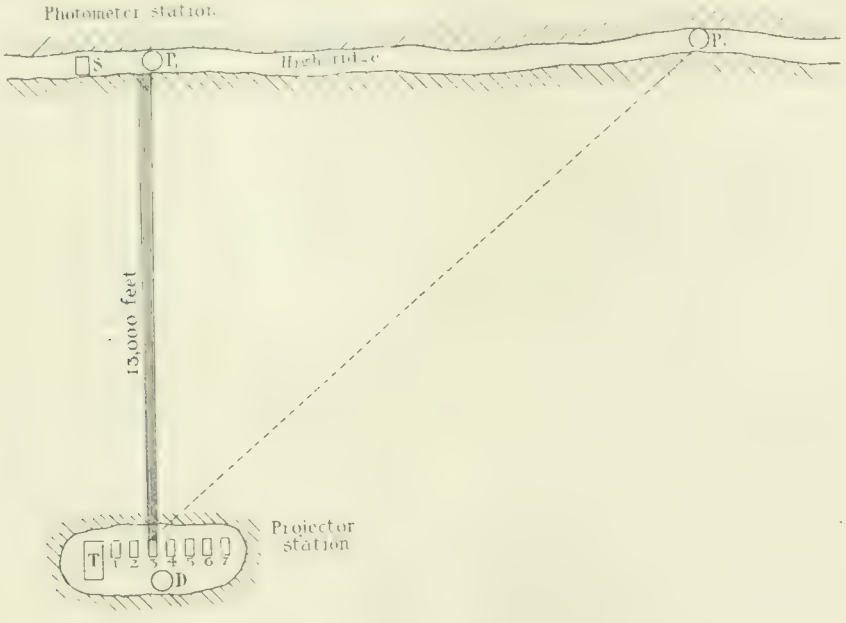


FIG. 6.—Plan of test station.

Every arc, mirror or other device tried was always tested against the standard of reference during the same atmospheric conditions on the interleaved system, and by taking a very large number of comparative tests we were able to form an accurate estimate of their relative capabilities.

11. The telephotometer which we used was calibrated indoors at short range. Lieut. H. C. Gibson was mainly responsible for the design of the instrument, the principle of which was that on looking through the eye-piece one saw side by side an image of the distant illuminated screen and an image of a small screen in the photometer itself. The illumination of the photometer screen could be varied by moving the source of illumination nearer or further along a graduated scale until the two images as seen through the eye-piece appeared of equal brightness. The scale was calibrated in foot-candles. The true brightness of the distant screen was measured by

were spaced to produce uniform illumination The screen was necessarily large, and its image in the telephotometer was the same size as that of the small screen.

The lumeters and the telephotometer lamp were tested against our secondary standards with great frequency and we had a long photometer bench rigged up in the open for such calibration, which was done of course in the dark hours.

12. In addition to this attempt to measure the atmospheric variations of transmissive powers we collected data of meteorological conditions—pressure, hygrometric state and direction and strength of wind. Continuous charts of local variations of these quantities were kept and the daily reports of the Meteorological Office were received. Lieut. E. S. White was responsible for this work.

After having analysed all our results of transmission

coefficients and compared them with meteorological variations we have been able to make some broad generalizations which may be of some value. We are not at liberty to publish these deductions as at present they are not considered to be of importance except for military purposes. The work is mentioned here to indicate that we recognized the difficulties which were referred to by Mr. C. C. Paterson and his co-authors in conducting tests through the atmosphere, and that we realized that it was necessary to obtain as much information as possible about atmospheric absorption. The author feels that much more may be done in this direction with advantage, and that any further work should have the active co-operation of the Meteorological Office.

Incidentally it may be mentioned that we essayed the task of measuring the beam intensity at long range at high elevation with the co-operation of an observation

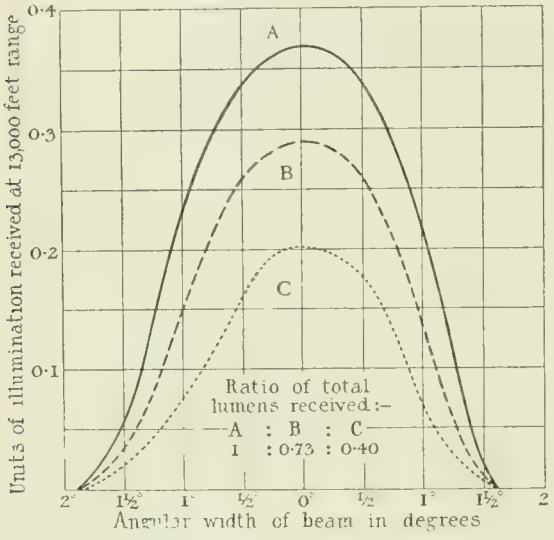


Fig. 7.—Illumination across the diameter of searchlight beams produced by arcs between three types of carbons, A, B, and C, of equal diameter and carrying equal currents. Range, 13,000 feet.

balloon section of the Royal Air Force. We had to abandon this method owing partly to the small number of nights on which we could use the balloon, but mainly to the swaying of the balloon and the resulting inability to take readings at any definite position of the beam. The little we did, however, indicated that there was no very great difference in comparative results obtained in this way and along the horizontal.

13. The results of the beam tests were plotted in graphical form showing candle-feet illumination received at the given range against the angular displacement of the beam. The total flux of light in the beam at that range was calculated from these graphs. It may be desirable here to explain that we had compared horizontal traverses with vertical traverses across diameters of the beam discs and found no measurable differences at long range. The effects of flame and obscuration effects of carbon carriers which show themselves at ranges up to 3,000 feet do not appear at 12,000 feet. We therefore assumed that the beam intensities as measured across the horizontal diameter would be the same across any other diameter, and we made calculations accordingly.

Fig. 7. represents a comparison of three different kinds of carbons run under identical conditions. They were of equal diameter and were run at equal currents in equal projectors. A is a plain solid carbon ("Apostle") whilst B and C are "impregnated" and also solid carbons (i.e. coreless). The curves represent the average of all the tests taken with these three carbons under the same conditions.

This comparison is of great interest in view of the fact that the National Physical Laboratory tests of these carbons showed that there was very little difference between them so far as the total flux of light emitted and the intrinsic brilliance were concerned when they were run at equal currents. Here is no question of 5 per cent; and but for the old warning that our eyes are not to be trusted a photometer would have been declared superfluous. It is highly probable that the poor results produced by impregnated carbons may be due partly to the absorptive effect of the fumes emitted and partly to the absorptive or reflective properties of the flame. Certain types of impregnated carbon searchlights are provided with a special forced ventilation; for example, the Sperry high-intensity light. With the particular form of impregnation used this forced ventilation is absolutely necessary. All forms of impregnation yet tried produce cloudy deposits on the front glass and on the mirror much more rapidly than do plain carbons, and such deposits have very high coefficients of absorption.

It can also be stated here that all impregnated carbons so far tested give a flame of much greater luminosity than that of plain carbons. Such luminous flame is decidedly disadvantageous in searchlight work, for it produces a widely dispersed secondary beam surrounding the main beam. This secondary beam is further of a flickering nature and its existence is a serious handicap to observation from the neighbourhood of the searchlight projector, whilst it has a further disadvantage of lighting up the foreground.

It may be concluded from all tests so far carried out that whatever may be the advantage of the flame arc over the plain arc for general illumination—whether considered from the point of view of absolute efficiency or of quality of light or of both—there is no question that the plain arc run at a current density of 0·31 ampere per sq. mm. is superior to that produced between any impregnated carbons yet tried at the same current density—whether the impregnation was introduced in a core or whether solid carbon was impregnated.

The points on the credit side are given in par. 15, but the balance on the debit side is too heavy.

The author does not include in the above generalization those special high-intensity arcs of Harrison, Beck and Sperry types which are well known in general principle, but even in these cases he submits that many claims made for them in the past have been too high because their beam-yielding capabilities were assumed to be proportional to their total flux of light or that comparative searchlight trials were made at short ranges. The

author regrets that he is not in the position to publish comparisons with the high-intensity arcs but hopes that some measure of publicity may be permitted in the near future.

14. Beams were also compared with one another over different ranges under the same atmospheric conditions in order to ascertain whether there were any difference in penetrating powers of the various arcs used. For these tests we had two photometer stations and, after measuring a beam at one station, it was swung over to the other and then back again to the first as a check on consistency. The ratio of the total fluxes received from the several beams at one range were compared with those at the other.

Comparisons were also made of various mirrors—mirrors of different sizes and focal length—glass and metal, gold- and silver-plated—all in terms of total flux of light received through the atmosphere.

The absorptive effect of the front glass and the extent to which draughts interfered with both the operation and the light-giving properties were also investigated.

Comparisons of searchlight beams were also made in terms of their finding power, that is their ability to throw sufficient light upon an aeroplane at various ranges to enable it to be seen by observers in the neighbourhood of the projector.

For this purpose several aeroplanes were placed along a high ridge, shown on Fig. 6, so that they had the sky as a background. They were placed square on to the projectors and elevated so that the planes were inclined at about 30° to the horizontal. The various beams to be compared were trained "on" the different targets in irregular order and, to prevent errors of imagination on the part of the observers, were sometimes trained "off" targets. At each exposure the observers noted whether they saw a target in a beam or not. These notes were compared with the director's tally which showed whether the beam was on a target or not, and if so what the range was.

After a long series of observations on different nights it was then possible to classify the various beams and to state the average range at which each might be expected to show up a target of the type used, as well as its maximum range.

15. It was to be expected that a controlled arc with a straight arc stream would be maintained to a greater length (i.e. distance between carbons) than an uncontrolled arc before going out. This is the case, and it is also true that the carbons have to be separated to a greater length on striking before a steady and quiet arc is maintained than is the case with an uncontrolled arc between larger carbons. This has the advantage of reducing the negative obscuration and, further, of being more amenable to control. A short arc is stiffer than a long one and the magnetic control necessary to act upon it would also be great enough to produce that boring tendency previously referred to, so we should not obtain a uniformly luminous crater except by still further reducing the size of the positive, when spindling would set in. Research on this point is now proceeding.

The relationship between the voltage across the carbon holders and the length of arc for constant current is of considerable interest. It was naturally expected that the voltage would increase as the arc lengthened, but the results obtained with carbons D, E and F shown in Fig. 8 are somewhat remarkable. D was a plain solid carbon, E and F were solid carbons of the same size impregnated with different mixtures.

These results were taken by striking the arc and opening out to the shortest distance at which it would run quietly. The carbons were then allowed to burn away, the current being maintained at the same value throughout, and the voltage and length of arc were taken at intervals.

The first point is that for a given arc length the voltage across the carbon holders is less with the impregnated carbons E and F than with the plain carbon D.

The second point is that in each case a certain length is reached when the potential difference suddenly drops, after which it rises again. This sudden drop was first discovered with impregnated carbons, because it will be noticed that it does not occur with the plain carbon D until an arc length of 55 to 60 mm. has been reached, which is beyond any useful length for the particular

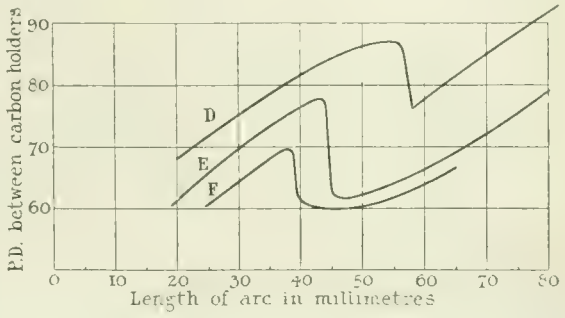


FIG. 8.—P.D. (across carbon-holders) of arcs between 3 different carbons, D, E, and F, at constant current of 200 amperes, and at increasing arc lengths—the arcs being under electromagnetic control.

current used. With impregnated carbons, however, it occurs at comparatively short lengths, depending on the quality and quantity of impregnating matter,

The author's first impression was that the point at which the pressure decreased represented a sort of "critical length" and that this would give the best working length and minimum power consumption for a given output. This was suggested by the fact that a decided change in the general character of the arc stream —or rather the "flame" surrounding the central stream —was apparent at the moment of the drop, and that the operator was always able to predict the drop without seeing the voltmeter. The behaviour of the plain carbon did not, however, support such a view, and we had almost decided that the phenomena only occurred with impregnated carbons when, on taking "that little more," we found it, but certainly beyond any working length.

One thing, however, is suggested by these curves, and that is, that if we project horizontally the point of lowest voltage at the length where the drop occurs, then the other point on the curve which has the same voltage does represent a working length at which the arc may be said to be stable.

For the moment these results must be left where they are. The author had not time to pursue these matters further as there were more immediate problems to be solved. He would say that if the carbons be gradually brought together again the curves do not exactly repeat and the lower voltage is maintained to a shorter length before rising again. It was difficult to get consistent results so far as the actual length at which the drop occurred was concerned, but the occurrence of the drop was quite consistent. It is essential that a perfect crater be maintained all the time, for unsteady conditions may cause sufficient variation in voltage to mask the effect entirely. This is especially the case with solid plain carbons, for at a length of 60 mm. the arc is beginning to be rather susceptible to draughts.

It will be noted that it was possible to run very long arcs before they went out, D and E being over 3 inches long. This indicates that a controlled arc of normal burning length of 35 mm. is not in any immediate danger of breaking, although it would break immediately if the controlling system were put out of action by short-circuiting it.

It is interesting to recall a similar sort of volts/length relationship for spark discharges between two electrodes. Sir J. J. Thomson in his "Conduction of Electricity through Gases" * says: "When a spark length falls below a certain value which we shall call the critical length the potential difference has a minimum value, and if the spark length is still further diminished the spark potential begins to increase and goes on increasing until the spark length gets down to about 10^{-4} cm. when it very rapidly diminishes."

16. Captain Haworth, Ph.D., undertook to investigate the characteristics of the controlled arc at the City and Guilds (Engineering) College by the kind permission of the Governors. He took voltage/current curves at different arc lengths on recording instruments. The arc was brought to its steady condition at normal current, and the current was then reduced until the arc broke. From the chart the volt/ampere and the watt/ampere curves were drawn. The voltage drop per millimetre length of arc at the normal current was also measured by allowing the carbons to burn away at constant current.

Considerable difficulties were experienced due to the supply of an insufficiently coppered stock of negatives, but Captain Haworth stated that within certain limits the equation was of the form $V = V_0 + \alpha l$, in which V is the voltage drop across the lamp, V_0 the voltage drop at the positive and negative arc contacts plus the drop in volts in the carbons, α the voltage drop per mm. of arc length and l the arc length in mm.

With a current of 220 amperes between plain carbon electrodes, the positive being 30 mm. diameter coppered and solid and the negative being coppered and cored of 16 mm. diameter, he found that the average value of V was $55 \cdot 8 \pm 4$ and α was $0 \cdot 44$ between extremes of 20 and 120 mm. As he points out, the voltage drop per mm. of arc length is much lower than that obtained by Mrs. Ayrton for low-current arcs, namely 2·07, and it may be due to greater concentration of the cathode stream and its probable higher temperature.

* Page 356.

17. The author has designed other forms of magnetic controls embodying the same basic principle but for different purposes.

It was early suggested that a system of iron poles electrically energized might be spaced around the inside of the projector barrel, and that variation in the strengths of these poles might be made instead of bodily movement of the original system in space. This was not, however, practicable in an ordinary barrel projector, but it has been tried with success on a special type now in process of development in which the temperature of the iron cores and the exciting windings cannot become very high.

A further form has been designed with a view to operating an arc between electrodes placed at 90° to one another, and this has also been found to work very well. The positive carbon has its axis coincident with the axis of the mirror, whilst the negative is at right angles to and beneath it. The idea here is to get rid of the negative obscuration, but as this is very slight the chief value lies—so far as searchlight practice is concerned—in the possibility of being able to use shorter focal-length mirrors and so collect a greater percentage of light. It should be also advantageous for projection work through a condenser which would afford an unobscured view of the crater. The right-angled arc burns very smoothly. A scheme of combining the electromagnetic control with a rotary field so that the arc stream was swept over the positive carbon face was also tried. It worked quite satisfactorily but did not show any particular advantages over the plain control; in fact the illumination produced was lessened.

18. The author would like to place on record his appreciation of the valuable help, suggestions and encouragement which he has received uniformly from Colonel A. E. le Rossignol, C.B., T.D., R.E. (T). He would also express his thanks to his colleagues of the Experimental Section, Lieutenants H. C. Gibson and E. S. White, and the other members of the personnel of that Section for all the help, enthusiasm, and effort which they put into the work.

Summary.

(1) With ordinary carbons (i.e. carbons free from any special salts or mixtures) an improved efficiency in terms of the flux of light per watt expended is obtained by running at higher current density.

(2) It is not possible to run an ordinary carbon arc with any degree of smoothness, steadiness or silence at a greater current density than 0·15 ampere per sq. mm. of the cross-section of the positive carbon, but if the arc stream be acted upon by a system of external magnetic forces tending always to keep it central, a current density of 0·31 ampere per sq. mm. can be attained with smooth and silent operation.

(3) A device for producing the necessary external forces is described.

(4) The use of this "control" renders the soft "core" generally to be found in positive carbons unnecessary and even disadvantageous.

(5) Ordinary solid carbons of greater diameter than 20 mm. must be copper coated in order to carry current

at the rating of 0·31 ampere per sq. mm. without becoming red-hot along their entire length.

(6) For arcs at from 80 to 300 amperes a cored copper-coated negative of such diameter that the current density is about 1 ampere per sq. mm. of its cross-section has been found most suitable.

(7) Whilst the impregnation of carbons with salts or other mixtures does make for smoother running in some cases and lowers the potential difference required for a given current and arc length in all cases so far tried, yet the total flux of light received in searchlight beams from such arcs at working ranges is much less than that from a plain carbon arc at the same current and current density, both absolutely and per watt expended.

(8) In view of the fact that the National Physical Laboratory tests with impregnated carbons showed that they were only very slightly inferior in intrinsic brilliance to ordinary carbons, the absolute importance of outdoor photometric tests over working ranges is emphasized. The methods adopted are described.

(9) The potential difference per mm. of arc length is lower with these high-current arcs than with the comparatively low-current arcs.

(10) The potential difference between the carbon holders for constant-current "controlled" arcs increases with the arc length up to a certain length, when it suddenly falls and then steadily increases again. Investigations of this have been done principally with 200-ampere arcs at lengths of from 20 mm. to 84 mm.

The drop in pressure occurs at a shorter length with impregnated carbons than with plain carbons.

MULTIPLE-UNIT SHUNTS FOR THE MEASUREMENT OF VERY HEAVY CURRENTS.*

By M. B. Field, O.B.E., Member.

(*Paper received* 16 *March*, 1920.)

An adequate appreciation of the limits beyond which a given design of mechanical or electrical contrivance is unsuitable, is a first essential of the engineer. Nevertheless, we may become wedded to some particular construction to an extent which, at a later period, astonishes us. We have been able to meet demands for increased duty, again and again, by the simple expedient of an all-round increase of dimensions, and we have become so accustomed to the permanence of the design that, on the advent of the stage of its growth when a complete breakaway from old associations is logically called for, we fail to recognize it and become responsible for some engineering monstrosity.

If we ask ourselves how we should proceed to construct a shunt for, say, 50,000 amperes, we recognize that the design at present in vogue, comprising two short cast-metal palms bridged by a number of high-resistance strips, or the equivalent, is impracticable. The difficulty of bringing 50,000 amperes to the palms and making adequate contact there, the uncertainty of the distribution of current throughout the mass, and our inability to test the unit at anything approaching full load, render such a proposition inadmissible.

We may then ask ourselves with advantage, firstly, if for 50,000 amperes the single-unit design be impracticable, how can we satisfactorily solve the problem, and, secondly, at what limit of carrying capacity should we be well advised to break away from the present-day design?

In the author's opinion, 6,000 amperes is about the practicable limit of carrying capacity of a single unit. Beyond this limit, the objections above enumerated, among others, render such construction incompatible with good engineering.

In the case of a 10,000 ampere shunt recently examined, it was found that with a given current flowing, the volt-drop between the potential terminals could be modified by as much as 4 per cent by varying the method of clamping the circuit-conductors to the palms. In this instance, the palms were short and badly designed, and the current-paths through the high-resistance metal depended in large measure on the terminal conditions.

A great improvement might have been effected by substituting arms provided with palms in place of the short squat palms, but the difficulty of testing the unit at a current approaching 10,000 amperes, to determine its constant and its temperature rise, would tax the resources of most manufacturers.

In this communication, the author discusses a multiple-unit shunt in distinction from the single unit as employed heretofore. He proposes to employ a number of standardized units or sub-shunts in parallel, so connected to a single milliammeter that the latter indicates accurately the sum-total of the current

* The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

traversing all the sub-shunts independently of the actual distribution of the total current among them. With such an arrangement the accuracy of the reading is unaffected by the nature of joints between the shunt-palms and the circuit-conductors, be they good, bad, or indifferent.

The scheme involves a number of sub-shunts, similar in respect that, with the same current traversing each, the volt-drop measured between the potential terminals is the same in each. The like potential terminals are

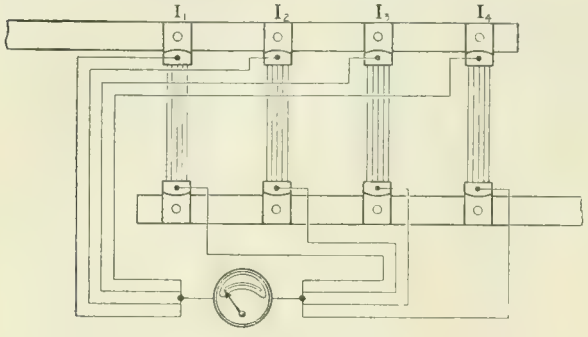


FIG. 1.

connected to star points by leads of equal resistance, termed equalizers, and the milliammeter is connected between the star-points.

The equalizers are generally conductors of small cross-section carrying small currents; they are not to be considered as conductors equalizing the distribution of current between the sub-shunts, but they operate in such a way that the potential difference at the star-points is proportional to (and very nearly equal to) the average potential difference existing at the potential terminals of all the sub-shunts.

Fig. 1 represents a simple 4-unit system; the milliammeter reads $I_1+I_2+I_3+I_4$. Fig. 2 represents a variation of the previous arrangement.

The advantages accruing from the system are various. Fig. 3, for example, shows the possibility of inserting a multiple-unit shunt in a run of busbars. The sub-shunts are neatly nested without loss of space; the total heat is distributed conveniently over a considerable region; each sub-shunt is readily accessible and removable, and is independently standardized. With the arrangement shown, it may be convenient to figure

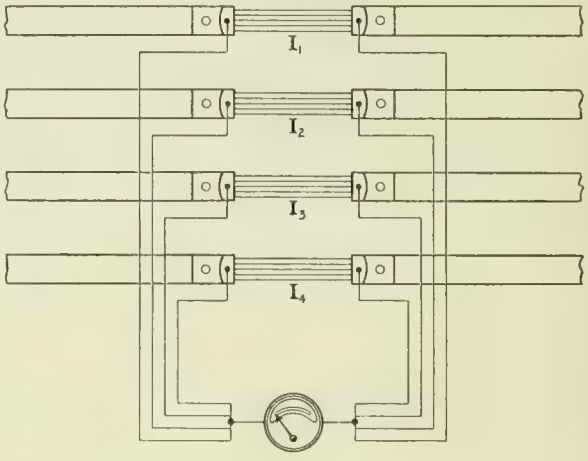


FIG. 2.

upon each busbar conductor, with its corresponding shunt, carrying 1,000 or 1,500 amperes.

Fig. 4 shows in greater detail a shunt suitable for insertion in a run of strip conductors. It comprises two lengths of copper conductor bent as illustrated and bolted together with insulated joints a J, J. While therefore, the shunt as a whole is sufficiently flexible to adapt itself readily to the surfaces of the contiguous conductors, it may be handled during the processes of testing, transportation and assembly on site, without fear of straining the joints of the high-resistance strips. S, S, represent the resistance strips; T, T, the potential terminals. High-conductivity metal is employed as far as the junction with the high-resistance strips. The sub-shunt actually forms a portion of the busbar or feeder-conductor and the usual method of jointing is employed.

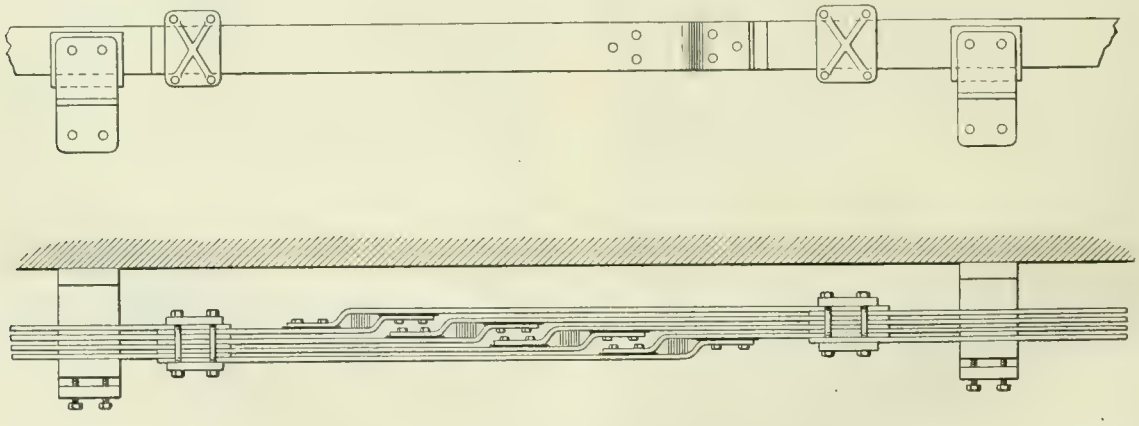


FIG. 3.—Horizontal arrangement of multiple shunt.

An interesting feature of the construction illustrated is that the current in any one sub-shunt is nearly uniformly distributed among the various high-resistance strips, the current-flow path through each strip being constituted by the same length of copper and strip, a feature which materially aids in standardization.

If we bear in mind that these sub-shunts replace a section of the circuit-conductor, that the cast-palms with the necessary machining are obviated, and that the usual jointing difficulties are entirely overcome without recourse to surfacing and so forth, we shall be prepared to admit not only that the design is sounder from the engineering point of view, but that it involves a saving of outlay.

Fig. 5 illustrates a portion of a special design for a 32,000 ampere shunt required for mounting on the wall of a generating station. It comprises eight stan-

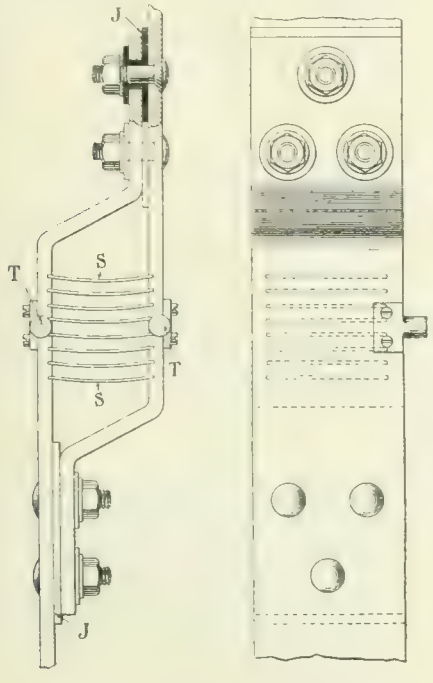


FIG. 4.

dardized sub-shunts of 4,000-ampere capacity each, two only of which are shown in the figure. Two copper tubes supported horizontally in wall brackets, but insulated therefrom by means of substantial micanite bushes, form a framework on which the sub-shunts are carried. "Hands" attached to the upper and lower limbs of each sub-shunt grasp the copper tubes as indicated and support the sub-shunts independently of the circuit conductors.

Incidentally, it may be mentioned that the sub-shunts are not insulated from the supporting copper tubes. While it is not necessary for the accuracy of the arrangement that the potential of the like ends of the various shunts should be the same, any partial equalizing effect is not undesirable, since it reduces the magnitude of the currents circulating in the equalizing leads to the star-points.

The following tests conducted in a laboratory on small-sized shunts in parallel are of interest in showing that the reading of the milliammeter, when suitably connected, is wholly independent of the distribution of current as between the various units.

Four 150-ampere shunts marked I, II, III and IV, were connected as indicated in Fig. 1. A standard ammeter was placed in series with the combination and a current of 400 amperes was passed through the circuit. The readings of the totalizing or summation ammeter were compared with those of the standard, while the screws securing the various shunts to the copper conductors were tightened and loosened so as to vary the relative distribution of the total current among the four individual shunts. The relative dis-

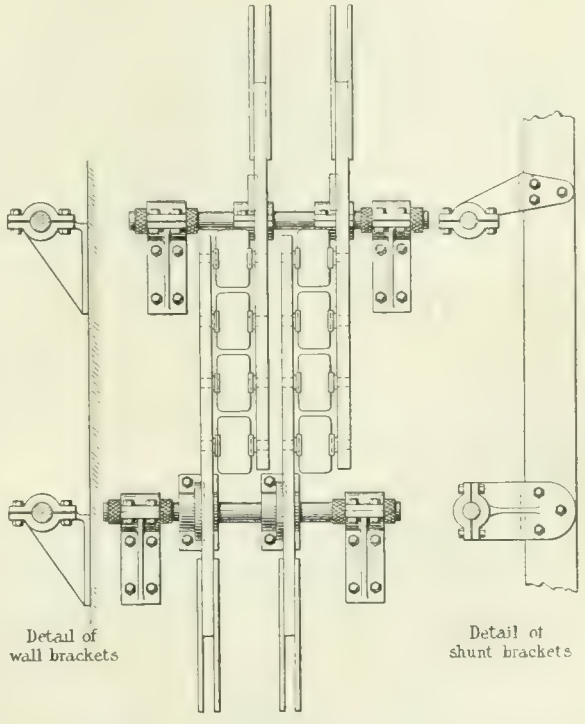


FIG. 5.—Vertical type of multiple shunt.

tribution of the current was determined by taking the millivolt drop across each individual shunt. Each equalizer consisted of about 24 inches of No. 16 copper wire.

The results shown in the Table herewith were obtained.

It will be observed that, within the limits of observation, the reading on the summation ammeter remained constant so long as the total current was maintained steady, quite irrespective of the goodness or badness of the contact resistance between the palms of the individual shunts and the main copper conductors, and, consequently, was independent of the actual distribution of the total current among the various shunts.

This test having been completed, all the screws were removed from the four shunts, and the shunts were merely laid across the copper conductors. Pre-

cisely the same results were obtained. Strong pressure could be applied to one shunt, while a slip of paper could be passed under the palms of another, and so on, but so long as the main current was maintained at 400 amperes, the summation instrument indicated the same reading under all conditions.

The author requested Mr. A. E. Moore of the College of Technology, Manchester, to make a number of independent tests. The results kindly furnished by Mr. Moore are to be found in an Appendix to this paper.

We may now, with advantage, look at the proposition from the analytical point of view.

Test	Main Current	Conditions of Shunt Circuit	Approximate Distribution of Current				Readings of Summation Ammeter. Constant of Combination 7·764	
			Shunt I	Shunt II	Shunt III	Shunt IV		
	Amps.		Amps.	Amps.	Amps.	Amps.	Millivolts	Amps.
I	400	All shunts tight	100	100	100	100	51·6	400·6
II	400	Some shunts loose	119	88	87	106	51·6	400·6
III	400	Some shunts loose	112	98	88	102	51·6	400·6
IV	400	*No. I shunt disconnected from main conductor, others as in III	9	132	123	136	51·55	400·2
V	400	*No. I disconnected from main conductor, other shunts tight	9	127	131	133	51·55	400·2
VI	300	*Nos. I and III disconnected, others tight	7	140	7	146	38·45	298·5

* Although certain shunts were disconnected from the main conductors they were still linked up to the other shunts in circuit by means of the equalizing connections, and thus by-passed small amounts of current.

There are three matters in relation to a shunt that we have to consider :—

Its "constant," denoted by the symbol K.
Its terminal resistance, denoted by the symbol R.
The electrical symmetry as hereafter explained.
[K and R are physical constants expressed in ohms.]

Suppose we pass I amperes through the shunt from palm to palm and measure the volt-drop between the potential terminals. The potential difference expressed in volts will be K I where K is the shunt "constant."

If we find that the potential difference varies according as we apply our circuit conductors to the palms, then K is variable, and it will be assumed that the design of shunt, with the employment of long enough palms, or with other precautionary means, is such that, for all currents passed from palm to palm, K has a definite value and is independent of the method of clamping the circuit conductors.

If we pass I amperes through the shunt *via* the potential terminals, and the volt-drop between the potential terminals is R I, R is the "terminal resistance" of the shunt. It is the resistance that would be measured on a Wheatstone's bridge if the shunt were connected thereto by its potential terminals. R and K may be practically equal in value or may be very different, depend ng on the design of the shunt.

K may be affected by the method of connection of the circuit conductors, but R cannot be so affected. Again, R may be affected by the length of the (potential) terminal posts, while such variation would have little or no effect on K.

R becomes very different from K when we are dealing with grids and the potential terminals are far removed from the palms, as in Fig. 6. Let us suppose that in this case the palms have negligibly low resistance, then we should obviously have $K = r/9$; $R = 7r/27$.

If, however, we modified the shunt to that shown in Fig. 6A by applying transverse plates of negligibly low resistance, we should not appreciably alter K, but R would become $r/9$.

The reason for the difference between the K and R values is that current passed through the shunt *via* the potential terminals assumes a totally different distribution from that which obtains when the current passes from palm to palm.

This matter becomes of importance if any appreciable current is side-tracked *via* the potential terminals. In such event, even if we know the current passing through the centre cross-section of the shunt, we can

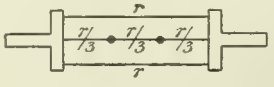


Fig. 6.

Fig. 6A.

take neither K nor R times this current as representing the potential difference at the potential terminals, because the side-tracking of current alters the current-paths within the mass of the shunt.

The current side-tracked by a milliammeter is so small that the above consideration may be disregarded, but that side-tracked by a mercury meter used in conjunction with a shunt may require consideration from the above point of view.

Again, it is conceivable that with the arrangement of multiple shunts there may be a considerable interchange of current between shunts *via* the equalizers, and we must satisfy ourselves that no error is introduced thereby.

Considering the simple case of a shunt where the current emerging from one potential terminal is equal to that entering at the other, as in Fig. 7, by the principle of super-position of current distributions we have:—

Potential difference at potential terminals $= K I - R i$.

In general, however, the case is a little more involved, since the currents entering or emerging at the potential terminals are not necessarily equal (see, for example, the case of the staggered multiple shunt in Fig. 3).

We may consider this more general case from the point of view of a network.

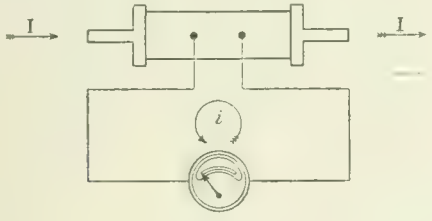


FIG. 7.

In Fig. 8 we have a network in two or three dimensions. 1, 2, 3 and 4 are current terminals embedded in the network each connecting to a great many contiguous meshes. These current terminals are to be considered as having definite dimensions (not merely points of the network), and of sufficiently great conductivity that all points of a given terminal may be considered to be at the same potential, i.e. any differences of potential that may exist are insignificant in comparison with those we are considering in the network

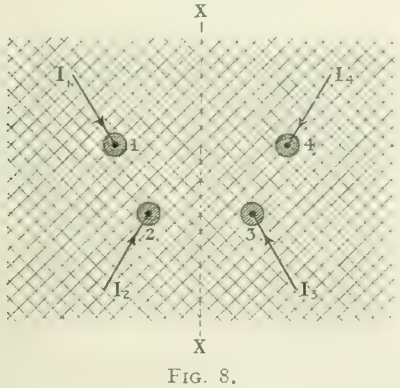


FIG. 8.

as a whole. This supposition implies that the distribution of current throughout the network will not sensibly depend upon the precise points of contact at the terminal surfaces where current is led in or withdrawn.

We further assume that the network and the arrangement of the terminals are symmetrical about the transverse plane X X.

Currents I_1, I_2, I_3 and I_4 enter the network at the four terminals 1, 2, 3 and 4, and these are the only currents entering or leaving. We have then the condition $I_1 + I_2 + I_3 + I_4 = 0$, or $I_4 = -(I_1 + I_2 + I_3)$.

Now we know that with these currents entering the specific network at the terminals there can be only one current distribution in the network.

Assume that we put I_1 in at 1 and withdraw I_1 at 4; a certain distribution results. Secondly, inject I_2 at 2 and withdraw an equal current at 4; a second distribution results. Lastly, inject I_3 at 3 and withdraw it at 4, and a third distribution results.

Let us further assume that these three distributions are superposed by injecting I_1 at 1, I_2 at 2, I_3 at 3, and withdrawing $I_1 + I_2 + I_3$ at 4 simultaneously.

We have then the condition with which we started, namely, currents I_1, I_2, I_3 and I_4 entering the network but subject to the condition that $I_1 + I_2 + I_3 + I_4 = 0$, and we see that the only possible distribution is that obtained by summing the three simpler distributions above named.

When I amperes are put in at 1 and withdrawn at 4, let the potential difference from 2 to 3 be $K I$.

When I amperes are injected at 2 and withdrawn at 4, let the potential difference from 2 to 3 be βI.

And when I amperes are injected at 3 and withdrawn at 4, let the potential difference from 2 to 3 be γI, where K, β and γ are constants of the network.

Then, obviously, when I_1, I_2, I_3 and I_4 are the currents entering the network, the potential difference from 2 to 3 will be $K I_1 + \beta I_2 - \gamma I_3$.

I_1, I_2 and I_3 are independent of each other; we can give them any values we like, and the above expression for the potential difference between 2 and 3 must always be true.

Let us then make $I_1 = 0$, $I_3 = -I_2$ (when, of course, $I_4 = 0$). The potential difference from 2 to 3 is then $(\beta - \gamma) I_2$.

But here we have I_2 entering the network at 2 and leaving the network at 3, and no other currents entering or leaving, and I_2 produces a potential difference $(\beta - \gamma) I_2$; hence $(\beta - \gamma)$ must be the resistance of the network between the terminals 2 and 3 which would be measured by a Wheatstone bridge. Call this resistance value R, and we have

$$R = (\beta - \gamma).$$

Again, since I amperes entering at 3 and leaving at 4 produce a potential difference from 2 to 3 of γI and the arrangement is symmetrical about the plane X X, it follows that I amperes entering at 1 and leaving at 2 will also produce a potential difference from 2 to 3 of γI.

By inserting in the expression $K I_1 + \beta I_2 + \gamma I_3$ the values $I_2 = -I_1$; $I_3 = 0$; we obtain, potential difference from 2 to $3 = (K - \beta) I_1$.

Hence $K - \beta = \gamma$, or $K = (\beta + \gamma)$.

From which we obtain—

$$\beta = \frac{K + R}{2}; \quad \gamma = \frac{K - R}{2}.$$

We may therefore write the potential difference from 2 to 3 in the form

$$K I_1 + \left(\frac{K + R}{2}\right) I_2 - \left(\frac{K - R}{2}\right) I_3.$$

If this be true of a network, it is true of a solid conductor symmetrical about a central transverse plane. We have made no assumptions regarding the size and complexity of the network, nor with regard to the resistances of individual portions of the network; hence our result applies equally to a hypothetical network the meshes of which are of microscopic proportions and so artfully arranged that the conductivity of the network (in bulk) is equal in all directions, while its specific resistance (in bulk) is equal to that of, say, copper, manganin or other material. For the purpose of our problem, such a network is equivalent to a solid conductor.

We may, therefore, apply this result to the case of our shunt. We assume as before that the main currents I_1 and I_4 are led into and away from the shunts at localities (corresponding to 1 and 4 of the network) so far removed from the high-resistance strips that the value of K is not affected by the precise method of introducing and withdrawing the current.

The terminals 2 and 3 of the network correspond to the potential terminals of the shunt.

K is the constant of the shunt;

R is the terminal resistance, as previously defined.

The potential difference at the potential terminals is then, as we have seen,

$$K\,I_1 + \left(\frac{K + R}{2}\right) I_2 + \left(\frac{K - R}{2}\right) I_3$$

where I_1 is the main current entering the shunt, I_2 and I_3 are the currents entering the shunt at the potential terminals.

Multiple Shunt.

With this preliminary, we are in a position to consider the multiple shunt.

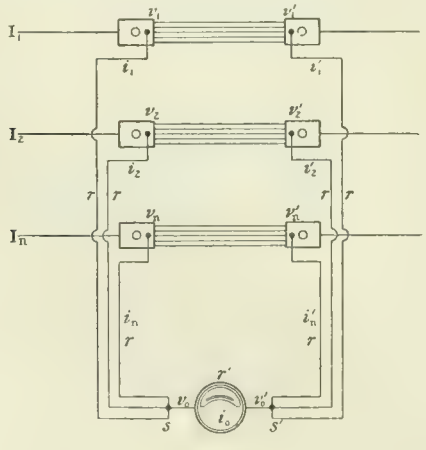


Fig. 9.

We will assume n conductors (Fig. 9) in parallel, each connecting to a similar shunt-unit having "constant" K, and "terminal resistance" R. The currents flowing in the conductors towards the shunts are I_1, I_2, etc., . . . I_n.

The potential values at the positive terminals of the shunts are v_1, v_2, etc., . . . v_n, and at the negative terminals v'_1, v'_2, etc., . . . v'_n.

Like terminals are connected to the star-points s and s' by equalizers of resistance r.

The potential values of the star-points are v_0 and v'_0; the milliammeter is connected between s and s' and the resistance of its circuit is r'.

The current through the instrument is i_0, so that $i_0 = (v_0 - v'_0)/r'$.

If we use the symbol Σ_1^n for the algebraic summation of n similar quantities, we have for the total current flowing in the group of conductors

$$\Sigma_1^n I = I_1 + I_2 + \ldots + I_n = \mathbf{I}$$
$$\Sigma_1^n v = v_1 + v_2 + \ldots + v_n$$
$$\Sigma_1^n v' = v'_1 + v'_2 + \ldots + v'_n$$

and so on.

The algebraic sum of all the currents arriving at s from the various shunts is equal to i_0 and this is equal to the current leaving s'.

We may write these conditions in the form:—

$$\Sigma_1^n v - n\,v_0 = r\,i_0$$
$$-\Sigma_1^n v' + n\,v'_0 = r\,i_0$$

Hence $$\Sigma_1^n (v - v') = 2\,r\,i_0 + n\,(v_0 - v'_0)$$

and $$\frac{1}{n}\Sigma_1^n (v - v') = \left(\frac{2\,r}{n} + r'\right) i_0$$

The expression on the left-hand side is the average potential difference of the shunt units, and we observe that i_0 is proportional thereto.

From our previous work, we can write

$$\Sigma_1^n (v - v') = K\,\Sigma_1^n I - \frac{K + R}{2}\Sigma_1^n i + \frac{K - R}{2}\Sigma_1^n i'$$

where $\Sigma_1^n i$ represents the algebraic summation of all the currents in the equalizers flowing towards s, and $\Sigma_1^n i'$ the algebraic sum of those flowing away from s'.

Now $$\Sigma_1^n i = \Sigma_1^n i' = i_0$$

Hence $$\frac{1}{n}\Sigma_1^n (v - v') = \frac{K}{n}\mathbf{I} - \frac{R}{n} i_0$$

and we have finally

$$\frac{K}{n}\mathbf{I} - \frac{R}{n} i_0 = \left(\frac{2\,r}{n} + r'\right) i_0$$

It will be seen that this is precisely the expression we should expect if all the shunt-units were conglomerated into a single large shunt.

K/n would be the new constant.

R/n would be the new terminal resistance.

$\frac{K}{n}\mathbf{I} - \frac{R}{n} i_0$ would be the potential difference at the shunt terminals.

$\frac{2\,r}{n} + r'$ would be the resistance of the milliammeter together with its leads.

We may, as usual, neglect the correction for the fact that the current i_o is side-tracked, and we then obtain

$$i_o = \frac{K}{2r + \frac{r'}{n}}\mathbf{I}$$

It will be seen that there is no difficulty in determining the equivalent resistance of the instrument leads due to the cat-o'-nine tails formation of the equalizers.

We assume that the equalizers form part of the instrument leads, that all the positive tail-ends are bunched together at a common terminal, and that the negative tail-ends are similarly treated. It then follows that the resistance of the instrument circuit is to be taken as that included between the common terminals at which the positive and negative tail-ends are bunched.

Or, we may look at the matter in the following light :—Since i_o is independent of the actual distribution of current among the shunt-units, we may consider the current equally distributed.

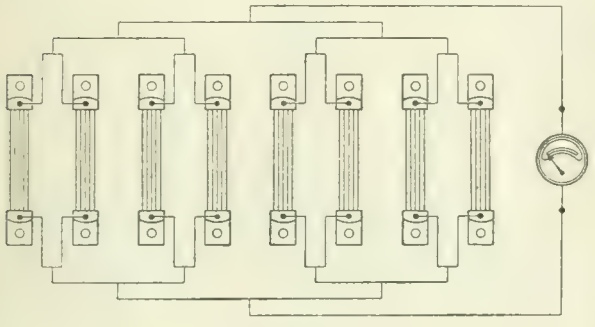


FIG. 10.

Again, since i_o is independent of any differences of value of v_1, v_2, v_3, etc., we may assume the case where these are all equal. This being so, v'_1, v'_2, v'_3 will be the same, and the group of shunts, though actually subdivided, may be regarded as a single unit with a number of potential terminals all at the same potential values.

It is clear that in such a case we should calculate the resistance of the instrument with its leads on the assumption that the tail-ends were all in parallel.

We may use any arrangement of equalizers, provided the path from the instrument terminal to each potential terminal is identical. Where the number of shunt-units is 4, 8, 16, etc., a convenient arrangement is shown in Fig. 10.

In any case, all we have to do in determining the equivalent resistance of the instrument leads is to consider the tail-ends bunched at common terminals, as explained.

A further matter of interest, though perhaps of small utility, is that shunts of varying carrying capacity may be assembled in parallel, the necessary conditions being that

$K_1 : K_2 : K_3$, etc., $= R_1 : R_2 : R_3$, etc., $= r_1 : r_2 : r_5$, etc.

that is to say, shunts having various K values may be paralleled provided their resistances, as also the resistance values of the corresponding equalizers are in the same proportion. A little consideration will suffice to show that this is so.*

In determining the cross-section of the equalizers regard must be paid to the possible differences of potential between their ends so as to avoid too great equalizing currents, and for this purpose it is as well to arrange that all the connecting conductors are well clamped together on either side of the group of shunt-units. Generally speaking, short wires of small section are sufficient for the equalizers.

Referring to the staggered arrangement in Fig. 3, consider two shunts displaced by 12 ft. The potential difference between like terminals will be of the order of 0·1 volt. A No. 14 manganin wire 12 ft. in length would have a resistance of about 0·5 ohm and the equalizing current would be of the order of 0·2 ampere.

The equalizers form part of the necessary "swamp" of the milliammeter and are not to be considered, therefore, as affecting the sensitivity of the instrument.

APPENDIX.

Mr. A. E. Moore has kindly supplied the following results of tests made by himself in the College of Technology at Manchester.

TEST 1.

Four 150-ampere shunts each having a K value of 0·0005052 ohm were connected in parallel, being bolted to busbars as in Fig. 1. Each potential terminal was connected to a star-point by a 10-ohm equalizer. The potential differences across the shunts, and across the star-points were measured by means of a potentiometer, while the main current was measured by means of the potentiometer connected to a standard 0·001-ohm resistance.

The average drop on the shunts (see Table 1) is, in all cases, very close to the drop between the star-points. It is to be noted, however, that when the shunts are not tight on the bars, the drop on an individual shunt is very variable owing to the changing resistances between the contacts at the bars and the shunt blocks. While it was not possible to get a steady observation of the potential difference on individual shunts with loose contacts, the potential difference across the star-points remained quite constant, no variation being detectable with the potentiometer. These remarks apply to all the observations made.

* The "constant" of the combination may be expressed in terms of the K, R values of any one shunt and the r values of the various equalizers, thus :

$$K_1\mathbf{I} = \left(R_1 + 2r_1 + r'r_1\Sigma_1^n\frac{1}{r}\right)i_o$$

Reference is called to Albert Campbell's paper on "Shunt Resistances and Temperature Compensation for Ammeters," *Journal I.E.E.*, 1905, vol. 35, and "Resistances with Current and Potential Terminals," by G. F. C. Searle, F.R.S., *Electrician*, 1911, vol. 66, pp. 999 and 1029, vol. 67, pp. 12 and 54.

TEST 2.

Observations (see Table 2, page 669) similar to those in Test 1 were made, but the potential terminals on the shunts were connected to star-points by means of short pieces of twin flexible copper wire, each about 75 cm. long, and of 70/40 strands.

A millivoltmeter was now connected to the star-points, and the following results were noted :—

Total Amperes	Millivolts	Remarks
496·6	62·33	Shunts as in C, Table 2
496·6	62·52	All shunts tight on bars

In the last set of observations the potential differences across the individual shunts were not noted.

There was subsequently reason to believe that the contact resistance at the ends of the flexibles, which were merely twisted together, was not so good as it might have been, and that the small discrepancies noted were in part, at least, due to this cause.

TEST 3.

In this case the star-points were made up with manganin wire, each piece being about 50 cm. long, and of No. 16 S.W.G.

The main current was again maintained at 496·6 amperes and the potential differences between the star-points were noted, with and without the millivoltmeter connected thereto (see Table 3).

The current calculated by dividing the millivolts in the last column by the resistance of the shunts =496·1 amperes.

It will be observed that the resistance of the equalizer leads were higher in this test than in Test 2 owing to the substitution of manganin equalizers for the copper flexibles. This accounts for the slightly lower reading of the millivoltmeter with the same total current passing. The resistance of the millivoltmeter was about 5 ohms.

TEST 4.

In this test, three 150-ampere shunts, and one 500-ampere shunt were connected in parallel to the copper distributing bars. The 150-ampere shunts were connected to the star-points by means of 10-ohm equalizers, and the 500-ampere shunt by 3-ohm equalizers.

A reflecting galvanometer was used as the millivoltmeter on the star-points.

Reading of Galvanometer	Main Amperes	Remarks
240	490·5	All shunts tight on bars
240	490·5	500-amp. shunt loose both ends
240	490·0	500-amp. shunt removed from bars
240	490·0	500-amp. shunt resting on bars
240	490·2	500-amp. shunt, one end tight on bar
240	489·7	500-amp. shunt, other end tight on bar
240	490·5	All three 150-amp. shunts loose, 500-amp. tight
240	491·5	All the shunts loose on the bars

TABLE 1.—*Observations in Test* 1.

	Total Current	P.D. on Shunts, Millivolts				Mean Shunt P.D.	P.D. Between Star-points	Current Calculated from Star-point P.D.
		(1)	(2)	(3)	(4)			
	Amps.							Amps.
A.	502·5	64·87	65·67	61·25	61·78	63·39	63·4	502
B.	502·5	81·2	80·9	86·1	5·7	63·47	63·4	502
C.	502·5	10·8	94·8	86·4	63·5	63·9	63·4	502
D.	502·5	79·37	0·0	87·87	86·8	63·51	63·4	502
E.	502·5	79·1	0·0	87·75	86·8	63·41	63·4	502

A. All the shunts were clamped tightly on to the copper busbars.
B. Shunt No. 4 was just laid on the bars.
C. All the shunts were just laid on the bars.
D. Shunt No. 2 was isolated from one bar, and tight on the other.
E. Shunt No. 2 was isolated from both bars.

TABLE 2.—*Observations in Test 2.*

	Total Current	P.D. on Shunts, millivolts (1)	(2)	(3)	(4)	Meanof P.D. on 1, 2, 3, 4	P.D. Between Stars	Current Calculated from Star PD.
	amps.							
A.	496·6	61·65	61·39	65·0	62·65	62·67	62·65	496·0
B.	496·6	110·9	2·3	117·3	17·9	62·1	62·45	494·5
C.	496·6	87·2	70·3	91·05	2·2	62·69	62·4	494·1

A. All shunts clamped tightly on to the copper busbars.
B. Shunts Nos. 2 and 4 laid loosely on bars.
C. Shunt No. 2 loose at one end and tight at the other, No. 4 isolated at one end and tight at the other.

TABLE 3.—*Observations in Test 3.*

	Total Current	Reading on Millivoltmeter	Potential Differences on Shunts (Millivolts) (1)	(2)	(3)	(4)	Mean Potential Differences	P.D. between Stars with Millivoltmeter	without Millivoltmeter
	Amps.								
A.	496·6	61·9	60·7	61·4	63·45	65·2	62·69	61·92	62·66
B.	496·6	62·0	18·2	55·3	87·75	89·7	62·74	62·0	62·75

A. All the shunts were tight on the copper bars.
B. All the shunts were just laid on the copper bars.

THE DEVELOPMENT OF THERMIONIC VALVES FOR NAVAL USES.

By B. S. Gossling, M.A.

(*Paper first received* 27 *May, and in final form* 4 *October*, 1920; *and read at a* Wireless Sectional Meeting *of* The Institution 23 *June*, 1920.)

Summary.

The first four sections of the paper describe the introduction of valves into naval wireless telegraph installations, and the early work, expe imental and theoretical, on the elucidation of their observed behaviour.

Section 5 deals with the principles of the numerical design of power valves, more particularly triodes, and with the rapid development of the manufacture of valves so designed.

The three following sections, 6, 7, 8, deal with the investigation and improvement of small valves for use in reception, including both high-vacuum and gas-filled types.

Successive stages of approximation in the calculation of the characteristics of small valves with low operating voltages are illustrated in section 9, the final result of calculation indicating the degree of closeness with which the observed behaviour of a high-vacuum valve can be accounted for in terms of known physical phenomena.

The concluding section deals with the standardization of valves and their specification for quantity production.

(1) Introduction.

The thermionic valve passed during the period of the war through all the various stages of the transition from an instrument the value of which was already recognized, but whose operation was erratic and theory obscure, to a product as reliable and as thoroughly standardized in manufacture as the incandescent lamp, and in addition capable, as regards all the main principles of its action, of explanation in terms of well-established principles of physical science, some of which had waited long for so definite an application.

This paper traces the course of this transition, as exemplified by the valves of various kinds with the development of which the wireless telegraphy departments of H.M.S. "Vernon," and later of H.M. Signal School, Portsmouth, were concerned.

The contributions of various laboratories and works to the work described amount to a considerable proportion of the whole, but the author hopes that, in the endeavour to distinguish such contributions, at least no injustice has been done.

Similarly, references are given to such published work, mostly of relatively early date, as influenced the course of development of the series of valves described, but no attempt has been made to refer to the considerable volume of work recently published.

The subjects of consideration relate to valves themselves, rather than to their mode of action in the electrical circuits in which they are used, and include the investigation of the special properties of valves of various kinds, and the methods of design, manufacture, and standardization, as far as these were developed. This treatment of the subject has necessarily made the current/voltage characteristics observed under steady current conditions the criterion both as to the phenomena within the valve, and as to its probable action in a given circuit.

Among the valves described as "high vacuum," that is, valves whose behaviour is in large measure independent of variations in such traces of residual gas as they may contain, those valves which are designed for power circuits providing operating voltages of hundreds or thousands of volts fall for many reasons into a class clearly distinct from the valves used in reception, where the operating voltages are measured by tens of volts, seldom nowadays by hundreds, and where the quantities of energy controlled by the valve are relatively minute.

If apology is needed for the space occupied by the description of "soft" valves, that is, valves whose action is dependent in one way or another on the presence of gas, it may be pointed out that no one can expect to understand the faults and limitations of so-called "high vacuum" valves who has not some understanding of the action of valves which contain gas in more than negligible quantity.

(2) The Application of Early Valves to Naval Wireless.

At the outbreak of the war one of the chief problems before the wireless telegraphy department of H.M.S "Vernon" was to find a good method of continuous-wave reception. This was more particularly pressing because Poulsen arc generators of various powers were already in a well-developed state. Small arcs had also been on trial as local oscillation generators for heterodyne reception, but small arcs tend to be more troublesome than large ones, and the smallest conveniently manageable at the time were of a power greatly in excess of what was really needed for use in reception. With these arcs, however, it had been clearly established that the use of the heterodyne itself gave enhanced sensitivity. It may be remarked here that the order of sensitivity so attained was deemed sufficient for all purposes in view, and there was no question at that time of developing amplifiers for use on any large scale.

Hence it was as a generator of low-power oscillations that the valve came to make its first appearance as a component of a naval installation. The advantages of eliminating the less steady of the two arcs, and at

the same time substituting a generator of a more nearly suitable order of power, were obvious from the first.

For heterodyne reception the existence and stability of the local oscillation are the important matters rather than its actual strength, and it seems in retrospect that this requirement was a very simple one to satisfy. Almost any triode valve will fulfil it if suitably connected. Indeed, this elasticity influenced the development of the valves up to a very late stage ; and rigidity of specification, for instance, was an unnecessary luxury as long as this simple requirement was the only one.

In the early days, however, the standpoint from which we viewed the valve and its ways was somewhat different. The first duty, and at the same time the first opportunity for beginning the study of the valve, was to examine and regulate the behaviour of certain concrete instruments. The two instruments receiving the most attention embodied respectively the ultraudion circuit (shown in Fig. 2) and De Forest "audion," and the Lieben circuit of Fig. 1 with one of Round's

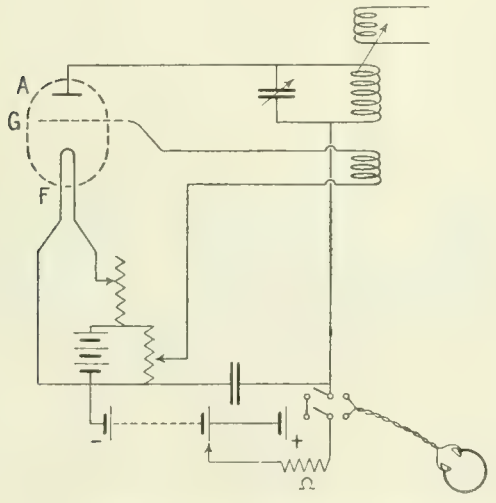


FIG. 1.—Lieben circuit heterodyne; Round valve.

earlier valves. Sets of this latter type, though eventually superseded, were in use to a considerable extent at one time. They had, however, the disadvantages of high anode voltage, excessive filament current, and the high mortality of platinum filaments working near their fusing point.

The first general principle to be thoroughly understood by us was that of the stability of the oscillation in this Lieben circuit, namely, that the resistance of the oscillatory circuit should be less than the product of the ratio of the mutual inductance to the oscillatory capacity into the rate of change of anode current with grid voltage. The establishment of this principle directly from the fundamentals of electro-dynamics by Professor Fortescue in December 1914, and its verification with the apparatus available, were a comforting beginning. Allied subjects of study were less promising. The internal action of the Round valves, with their relatively high gas pressure, high anode voltage, and necessarily extremely close grid is very complex, and to this day the author makes no claim to any clear comprehension of it. This valve is mainly dependent on a true multiplication of the ionic current by collision, giving poor results unless the gas pressure is high. Now most people who have taken up the study of valves have tended to exaggerate the importance of positive ions derived from the gas. The properties of this particular valve went to confirm us in this error for some considerable time. That was one source of difficulty. The electro-dynamics of the ultraudion circuit, again, are by no means so simple as those of the Lieben, even when all the essential electrical components are recognized. The inventor's diagram does not show them all, and one at least, of the greatest theoretical importance, had to be separately discovered. Further, the soft audion was a bad valve for use in

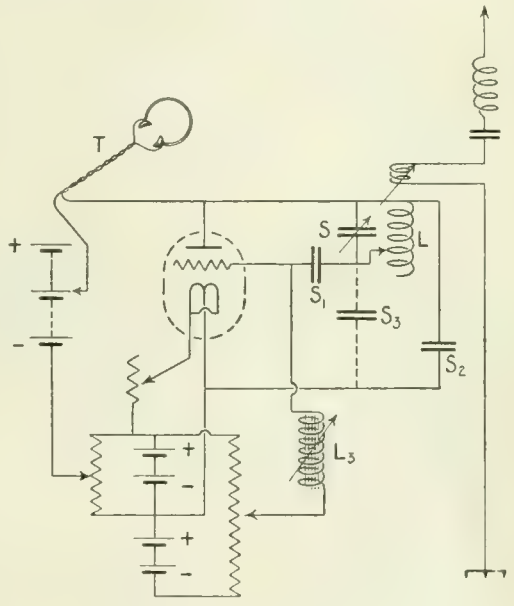


FIG. 2.—Modified ultraudion receiver; audion or R2 valve.

careful experiment. In this valve, as was demonstrated by G. B. Bryan at Greenwich in the winter of 1914–15, the equilibrium determining the amount of free gas present in the valve at a given moment was very easily disturbed by any marked change in adjustments. Reliable direct-current characteristics and other similar observations on the valve itself were difficult to obtain. However, the complication of the circuit would in any case have obscured the real connection between the characteristics of the valve and its functions in operation. The sets of this type were developed by direct trial using the audion as then available. The circuit seems peculiarly suited for use with valves of varying properties, and a good deal of solid progress was possible in spite of ignorance of the principles concerned.

The "missing link" in the circuit diagram was the capacity S_3 in Fig. 2 from the grid side of the oscillatory circuit to the filament, that is, usually to earth. The importance of this became sufficiently obvious experi-

mentally. If, as at first, it was left as a mere distributed capacity of leads, ends of coils, etc., the set was fickle in action, oscillations coming and going with the movements of the hand of the operator. Such occurrences were common enough in later work, and we were perhaps lucky in starting with an example the cause of which was so easy to run to earth. The insertion of an actual capacity, even though as little as 20 micro-microfarads, gave a marked improvement in stability and was embodied in various naval sets of this type. Re-arrangement of the circuit diagram eventually provided the explanation of the action.

at radio frequency in L and S, and the other at audio frequency in T, L_3, S_1. The advantages, such as they are, of reaction at audio frequencies were therefore available.

In the fully developed circuit of Fig. 2, therefore, a single valve acted as generator of radio-frequency oscillations and rectifying detector with reaction amplification at audio frequency for one beat note, and, it may be added, for one value of the coupling between the aerial and secondary circuits. This circuit was singularly little perturbed by changes of wave-length or of valve characteristics, these last being particularly

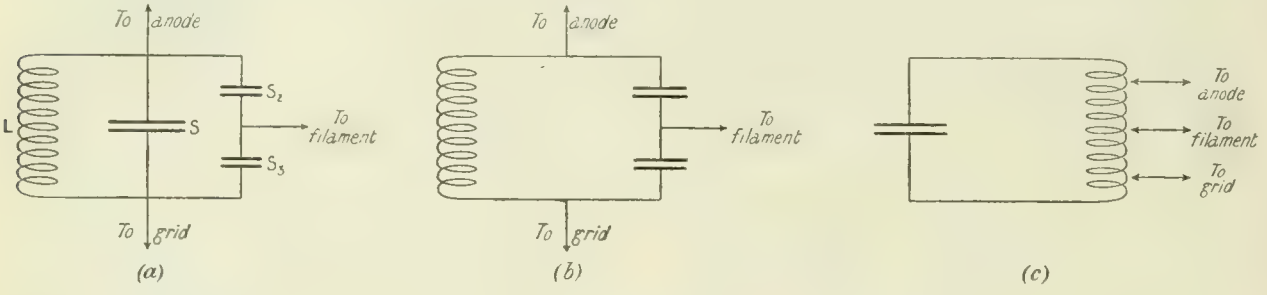


FIG. 3.

The circuit of Fig. 3 (*a*), so obtained, is clearly analogous to that of Fig. 3 (*b*), and this again to the generalized oscillatory circuit of Fig. 3 (*c*), the action of which is explained in one of Fortescue's recent papers.* In Fig. 2 will be seen a choke coil L_3 of some henries' inductance between the filament and grid. This was added to the original ultraudion circuit with the object of controlling the grid potential without disturbing its radio-frequency action, but it also provided the first

variable in the early audions. Still, a receiver of this sort, covering a wave-range of 300 to 10,000 metres and prepared for valve variations, had an elaborate wiring diagram and many operating handles. It was not a good form for introducing a novel type of instrument. Its versatility had uses, however; for when a shortage of audions at one time occurred the resourceful obtained serviceable results with the "Q" valve,

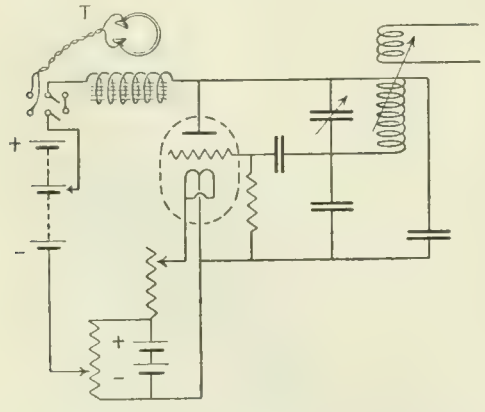


FIG. 4.—Modified ultraudion heterodyne; audion, R2, or R4 valve.

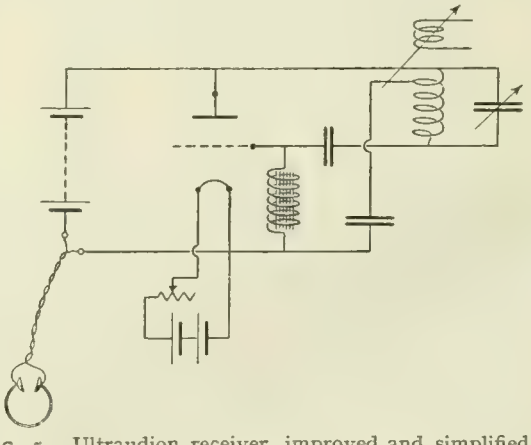


FIG. 5.—Ultraudion receiver, improved and simplified; Q or R4 valve.

example known to us of the circuit of Fig. 3 (*c*), of which this inductance L_3, together with that of the telephones T, and the capacity of the grid coupling condenser S_1 form the essential components, the remaining circuit components in Fig. 2 being inactive at audio frequencies. The receiver could be adjusted in such a way that two sets of oscillations were simultaneously produced, the one whose characteristics differ extremely from those of the soft audion.

Simplifications of this circuit were therefore made at different times. The first was a simplification of function, and simple heterodyne sets were made (Fig. 4) for use with a crystal detector, leaving the spark reception circuits practically untouched. These sets, it will be seen, employed the capacity-coupled circuit

* C. L. FORTESCUE: *Radio Review*, 1919, vol. 1, p. 83.

of Fig. 3 (*a*) and call for no comment here, except that with them was done most of the continuous-wave reception in both small and large vessels. Later sets were simplified as regards operation, retaining the full multiple functions of the valve. They took the form of Fig. 5, which is the same as Fig. 3 (*c*) with the audio-frequency circuit superadded, and showed in many ways the advantages that come with a clear comprehension both of how a set works, and of what purpose it is intended to serve. Such improvements in style are of slow growth; in this case study of the valve, with which this paper is chiefly concerned, was one of the essentials.

(3) Preliminary Experimental Studies.

So much, then, may be said about the circuit arrangements which were employed when valves first came into service use. For the functions of the valve in some of the circuits later developed reference can be made to three papers already published by Professor Fortescue.* We now pass on to work in what is, in most of its aspects, an entirely different field. This is the study of the mechanism of electrons, ions, electrostatic fields and so forth, the action of which, sometimes intricate, sometimes simple, underlies the observed electrical characteristics of valves of various types.

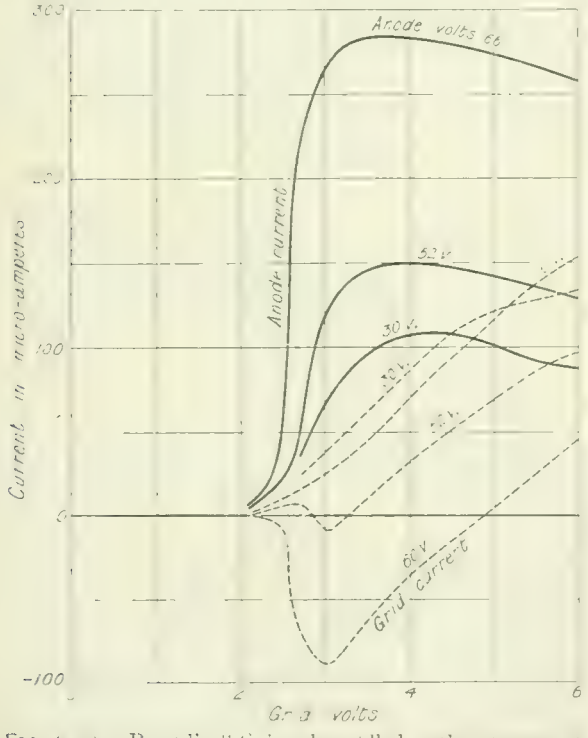


Fig. 6 (*a*).—Round's "C" valve, filled with nitrogen at 0·31 mm. pressure.

As already mentioned, the start was made in the direction of what proved to be somewhat of a cul-de-sac. However, we struggled along for some distance with the investigation of the Round valve, and found out a good many things besides our immediate object, which was the effect of the positive ions from the gas, the peculiar importance of which is perhaps confined to valves of this type.

The valves as received sometimes contained much too little gas, and to get any action at all the filament had to be over-burnt to a very dangerous extent. An investigation of the amount of gas actually required was planned and, in the case of nitrogen gas, was carried through, the valve being connected up for the purposes of the experiment to a special Sprengel pump, McLeod gauge, and gas-filling apparatus. The construction of this piece of plant was the occasion of some superhuman efforts in the way of glass-blowing under difficulties on the part of Lieutenant (now Lieut.-Colonel) Morris Airey. The so-called coal-gas came from a cylinder, usually much too eagerly, and no two pieces of tubing had the same working properties. The tangible results are summarized in some specimen characteristic curves shown in Figs. 6 (*a*) and 6 (*b*), and were confirmed by precisely similar work carried out at the National Physical Laboratory.

At the same time, however, it was brought home to us, and an attempted extension of the work to the more difficult case of the audion went to confirm the view, that the rapid solution of problems relating to the inside of the valve was a full-time occupation for someone working under very different conditions, and with very different equipment from any which could be contemplated on board the "Vernon." Still, laboratory work was an essential and we were very fortunate in our opportunities for furthering it.

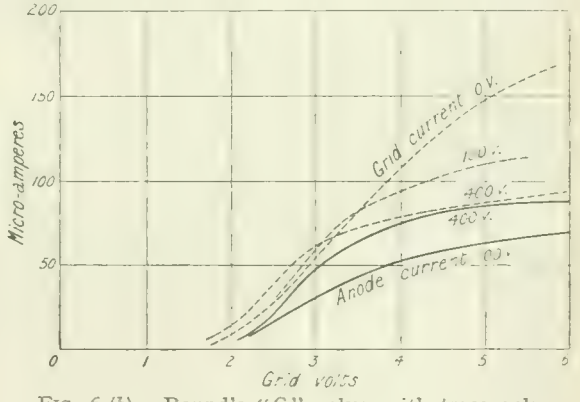


Fig. 6 (*b*).—Round's "C" valve, with trace only (0·0025 mm.) of residual gas.

Ever since the autumn of 1914, work on valves had been going on under Sir J. J. Thomson at the Cavendish Laboratory, Cambridge, where the experiments of Wright and Ogden, and later of White, led up to the "White" valve. With this work "Vernon" had been generally in touch, and it was just when we had arrived at a proper sense of our own difficulties that Sir J. J. Thomson suggested arranging for Mr. G. Stead to devote his whole time to valve work at Cambridge. This solution of the laboratory difficulty marked a new stage in the work of valve development. Hitherto we had

* C. L. Fortescue: (1) *Proceedings of the Physical Society*, 1919, vol. 31, p. 319; (2) *British Association Report* 1919; *Radio Review*, 1919, vol. 1, p. 83; (3) *Journal I.E.E.* 1920, vol. 58, p. 65; *Radio Review*, 1920, vol. 1, p. 178.

had little opportunity of, as it were, getting inside any valve. We had been content with comparing the construction and external electrical properties of sundry types of valve. To use a medical metaphor, the anatomy and comparative physiology of the article had progressed, but what we were now able to embark upon was the experimental physiology, not to say vivisection, and, as might be expected, we found plenty to learn.

Stead's early experiments, like those of others working on similar lines, were with valves having electrodes which were movable from the outside. The results began to dispel the prevailing fog, but were not fully appreciated until later. Progress with the technique of valve making, however, soon made possible a series of investigations of the audion under conditions of high vacuum, and also when filled with various gases under various pressures. These experiments showed how wide were the variations existing and permissible in the audion. They were contemporaneous with the beginning of the manufacture of valves of this type in England. This was undertaken in the summer of 1916 by the British Thomson-Houston Company, at Rugby, Mr. R. C. Clinker submitting some samples which, while generally as good as the original, were a considerable improvement on the original in respect of working life.

(4) The Calculation of the "Grid Constant."

At this stage we were still a long way from a comprehension of what was going on inside any valve. This was perhaps not surprising considering that we were proceeding in a physical problem by the methods, to revert to the former metaphor, of physiology rather than those of physics. Phenomena were observed, and measurements made when possible, and some attempt was made at correlating results, but there was as yet no numerical analysis of the figures obtained in the light of established physical theory. In dealing with an instrument containing so many component parts the geometrical form of which largely determine its mode of action, a theoretical basis of this kind is immensely preferable to a large collection of empirical formulæ. As it turned out, the materials for making a start were soon available. These were various specimen valves of types showing a closer approach to a thorough and permanent exhaust, judged by modern standards. There was the oscillion, of which more is to be said later in connection with power valves; but the valves from which the most illuminating data came were some small high-vacuum valves examined in the summer of 1916. These were a few audions exhausted by some improved process, but ordinary as regards the use of the flat plate and zig-zag grid, and together with these audions a valve of the kind which later became so familiar, the cylindrical "French" or "R" valve, as our Army later called it. In spite of the marked differences in their construction, these valves gave current/voltage characteristics which were very closely identical. This was enough to confirm that the form of these characteristics was governed by principles more fundamental than, let us say, the use of any particular form of electrode. For the elucidation of one at least of these principles all was ready.

One of the first things to attract the notice of most observers of the characteristics of well-exhausted valves is the fact that, if curves are drawn showing the variation of anode current with grid voltage for successive fixed values of the anode voltage, the grid voltage being the variable plotted horizontally as in Fig. 7, the effect of changing from one anode voltage to another is simply to displace the anode-current curve without sensibly altering its form. This implies that the anode and grid voltages are in a sense interchangeable; a given increase of anode voltage, for instance, can be counteracted by a corresponding change of grid voltage, which latter change is the same at all points of the curve. Mathematically speaking, whatever be the formula expressing the relation between the anode current and the two voltages, the anode voltage e and the grid voltage e' must always occur together and in an expression of the form $e/m+e'$. The quantity m in this expression is thus a "constant of the valve" independent of its current and voltage adjustments. To be able to explain this theoretically, and to calculate it numerically in certain practical cases, was as comforting a first fruit, in valve theory and design, as had

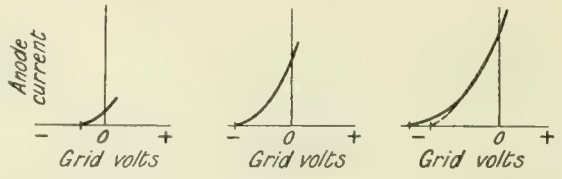


Fig. 7.

been the similar achievement for the Lieben circuit already mentioned.

When this effect was first observed by us, in the oscillion, the negative movement of the curve on raising the anode voltage was ascribed to a penetration into the neighbourhood of the filament of lines of force—electric force—derived from the anode and opening a direct path from filament to anode for the electrons emitted by the filament.

Experiments illustrating this by the analogy of current lines in a conducting sheet were suggested to Mr. Stead, but actually called forth something far more valuable. This was the communication by Sir J. J. Thomson of a formula giving the proportionate effects produced at the surface of the filament by the grid and anode voltages. The case given was that of a cylindrical anode and a grid of parallel wires spaced round a smaller circle. In the notation most familiar to those who have used it this formula gives the constant m as

$$m = \frac{\pi \, \mathrm{N} \, d' \log (d/d')}{\log [1/(\pi \, \mathrm{N} \, d_g)]}$$

where d and d' are anode and grid diameters respectively, and d_g the diameter of the grid wires which are spaced out at N per cm., whether round the circumference of the grid cylinder as in Fig. 8 (*a*), or as successive turns of a helix as in Fig. 8 (*b*).

A corresponding formula for plane anode and grid with a plane instead of a filamentary cathode can be obtained from Maxwell's " Electricity and Magnetism," 1892, vol. i, p. 312, but as cathodes of tungsten in the form of an incandescent plane do not occur in valves, it was to the cylindrical formula and the specimen French valve lent by Captain C. S. Wright, R.E., that we owed the establishment of this first point of primary importance in the theory of the triode valve. In the French, as in many other later valves of cylindrical form, the observed and calculated values of m agreed within about 10 per cent, so one property at least was shown to be calculable. For

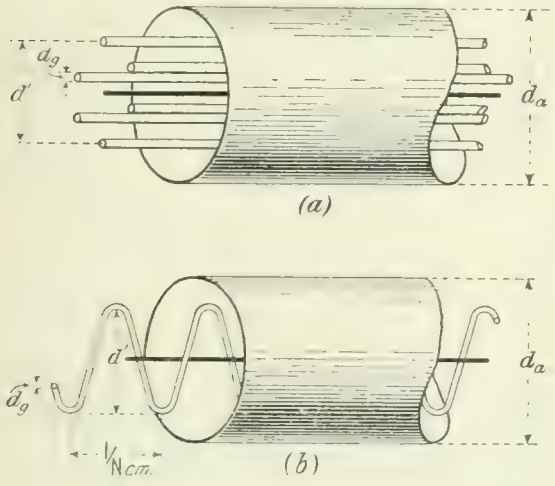


FIG. 8.

the small valves it was, as a matter of fact, for a very long time the only calculable one, but in another direction we were more fortunate.

15. THE DESIGN AND DEVELOPMENT OF POWER VALVES.

The design and manufacture of larger valves for use in the power circuits of transmitter sets, and handling powers of the order of $\frac{1}{2}$ kw. per valve, was fortunately a much more straightforward affair than the development of new types of receiving valves. Indeed the next chapter of the history of valve development dealing with these larger valves was in point of time extremely short, a period of four or five months in the winter of 1916–17 covering all the main points, theoretical and practical. On the practical side our preliminary experience had been satisfactory as regards circuits, tantalizing as regards valves. Oscillions had been difficult to obtain and barely up to the desired standard of reliability. An attempt to obtain a supply of valves of this sort from a source in this country for use in a 100-watt aircraft set developed by Lieutenant Morris Airey did not make rapid progress. On the other hand there was a single large pliotron, obtained from the General Electric Company of America, capable of handling some 700-watt power input, and showing that the development of valve transmitting circuits was likely to be a straightforward matter and that the real need was simply for valves.

On the theoretical side we were by then well provided with material relevant to the problem. We had had enough experience of the effects which progressive improvement in the exhaustion of a given valve produced on its characteristics to appreciate the conditions to which Langmuir's work on the " pure electron discharge " might be expected to apply. The main principles of the electrostatic action of the grid were established, as we have already seen.

In the Schenectady publications again, there was information in a strictly practical form concerning filaments for use as sources of electron currents, and more yet of the same sort was available.*

With so much thoroughly worked out and verified there was, it was found, only one small addition required to bring all together into a theory sufficiently complete for the design of triode valves, provided only that they should operate at voltages 10 or more times those in use for receiving valves. This was to introduce into Langmuir's formulæ for the value of an electron current, when the determining factor is the field applied to draw it away from the filament, terms enabling the composite field due to anode and grid acting together to be substituted for the field due to the single collecting electrode in the diode cases covered by the Schenectady formulæ. The composite field could, it was found, be considered to be equivalent to that set up by a single continuous electrode the surface of which was a plane or cylinder passing through the centres of the grid wires, provided that this electrode was at a potential

$$\frac{e'm + e'}{1 + 1\,m}$$

Taking this in conjunction with the formula for the rising portion of the characteristic of a high-vacuum diode, it was now to be expected that under conditions normally obtaining in transmitting valves the cathode current I, i.e. the total number of electrons leaving the filament, in a cylindrical valve would be given from the given dimensions of the electrodes, and the various combinations of the two potentials by the equation,

$$I = 2{\cdot}92 \cdot 10^{-6} \frac{l_f (e'm + e')^{3/2}}{\beta^2 d' (1 + 1\,m)^{3/2}} \text{ amperes}$$

where l_f is the length of the filament system measured along the axis of the concentric electrode cylinders. Also, this amounts to establishing that under conditions that the grid current is negligible, i.e. as long as the grid is negative or not very positive to the filament, the whole of the cathode current goes to the anode, giving an anode current,

$$I = 2{\cdot}92 \cdot 10^{-6} \frac{l_f (e'm + e')^{3/2}}{\beta^2 d' (1 + 1\,m)^{3/2}} \text{ amperes}$$

This was the general formula taken as the basis of the design of the characteristics of transmitting valves.

The anode-current grid-voltage slope k_1 or $d\,I/d\,e'$,

* DUSHMAN: *General Electric Review*, 1916, vol. 18, p. 150; and LANGMUIR: *Physical Review*, 1916, vol. 7, p. 302, and 1913, vol. 2, p. 450.

is obtained in regions where the grid current is negligible by differentiating with respect to e', obtaining :—

$$k_1 = \frac{3}{2} \cdot 2{\cdot}92 \cdot 10^{-5} \frac{l_f}{\beta^2 d'} \frac{(e\,m + e')^{1/2}}{(1 + 1\,m)^{3/2}}$$

$$= \frac{3}{2} \cdot \frac{\mathrm{I}}{e\,m + e'}$$

The anode current slope, k_2 or $d\,\mathrm{I}/d\,e$, is similarly

$$k_2 = \frac{3}{2\,m} \cdot \frac{\mathrm{I}}{e\,m + e'} = \frac{k_1}{m}$$

The ratio k_1/k_2 of the two slopes being equal to m.

Our information was less complete as regards the saturation value of the electron current emitted by the filament. This determines the height of the horizontal portion of the characteristics reached when a sufficient positive voltage is applied to either electrode, and is itself determined by the area and temperature of the filament surface, but we were fortunate in receiving from Professor O. W. Richardson in January 1917, just when it was wanted, a copy of a set of curves made for him from the elaborate collection of numerical data relating to tungsten filaments published by Langmuir some months previously.*

By adding suitable curves giving, from Langmuir's figures published elsewhere,† the specific electron emission of his tungsten, we became able to calculate the dimensions of filaments to give stated electron currents at stated working currents or voltages and at known temperatures, always provided that the corrections to allow for the cooling of the ends of the filament should be negligible. This was luckily not far from being true, as later demonstrated by Stead,‡ for the 15- or 20-volt filaments which we then had in mind. But in any case, since even the preliminary design of an idealized filament without end cooling adds three more variables, namely the length and diameter of the filament wire and its temperature, to those already enumerated, one would necessarily begin by designing a valve with an ideal filament as a first approximation. Re-arrangements of Langmuir's formulæ are then often useful for bringing together into close juxtaposition the quantities considered to be of particular importance in any given design. For instance, if the length of the filament wire and the voltage of the heating supply are considered more important than the corresponding wire diameter and heating current, the formula

$$l_f^{3/2} = \frac{\mathrm{E}_f}{\mathrm{E}'_f} \sqrt{\left(\frac{\mathrm{I}_e}{\mathrm{I}'_e}\right)}$$

obtained by eliminating the diameter and current from the primary expressions is useful. Here the quantities accented, E'_f, I'_e, are the heating voltage and electron emission for a tungsten cylinder of unit length and diameter, and are functions of the temperature, their value being obtainable from Langmuir's tables or Stead's curves. Again, if the heating current is of special importance the corresponding formula

$$l_f^{3/2} = \frac{\mathrm{I}'_f}{\mathrm{I}_f} \left(\frac{\mathrm{I}_e}{\mathrm{I}'_e}\right)^{3/2}$$

would be used in determining the length of the filament wire, or its working temperature. After the length of wire which will be available has been so determined, the possibilities of looping or coiling it so as to build up a filament system of axial length l'_f suitable for giving the proposed characteristics according to the anode-current formula already given can be considered.

Collecting them together, the main formulæ for the design of a power triode valve are

$$\mathrm{I} = 2{\cdot}92 \cdot 10^{-5} \frac{l'_f}{\beta^2 d'} \left(\frac{\mathrm{E}\,m + \mathrm{E}'}{1 + 1\,m}\right)^{3/2}$$

$\frac{l_f}{l'_f}$ = factor determined by construction of filament system

$$l_f^{3/2} = \frac{\mathrm{E}_f}{\mathrm{E}'_f} \sqrt{\left(\frac{\mathrm{I}_e}{\mathrm{I}'_e}\right)}$$

$$m = \frac{\pi\,\mathrm{N}\,d' \log (d_a/d')}{\log [1 + (\pi\,\mathrm{N}\,d_a)]} \quad \text{[see Figs. 8 (a), 8 (b)]}$$

Here the quantities usually determined by external considerations are the two supply voltages E and E_f, saturation current I_e, and ratio of saturation current I_e to anode current I_a at zero grid potential. The temperature of the filament then determines its life, and the dimensions of the anode surface give the limit of power that can safely be dissipated in the valve. Of the remaining quantities, the length and form of the filament system and the diameter of the grid are usually fixed by mechanical considerations. In the final design the only quantities in respect of which there is much range of choice are usually found to be the diameter and spacing of the wires of which the grid is built up.

A numerical example will illustrate the values likely to be arrived at for the various quantities which represent in the formulæ given the various dimensions of the three electrodes.

Suppose that we have to design a valve for an anode supply at 1,500 volts, and a filament supply at 20 volts, the anode being so dimensioned as to dissipate by radiation the energy of impact of the electrons constituting the anode current at the rate of 250 watts, without its temperature being raised sufficiently to impair the vacuum. Suppose also that the anode current at zero grid potential is to have the value 0·17 ampere, the anode being at 1,500 volts, and the power in the anode circuit being therefore 250 watts. This valve will evidently be just safe should the oscillations in the circuit which it has to feed be interrupted. Again, when the oscillations are taking place the anode current will vary with the grid potential, but its mean value will usually not exceed one-half of the saturation current given by the filament. If we choose a saturation current of 0·34 ampere, the mean power taken from the high-voltage supply happens to be 250 watts

* Langmuir : *Physical Review*, 1916, vol. 7, p. 302.
† Langmuir : *Physical Review*, 1913, vol. 2, p. 450.
‡ G. Stead : *Journal I.E.E.*, 1920, vol. 58, p. 107.

again, and as some of this will be dissipated in the oscillatory circuit the power lost in the valve will be less than 250 watts. This valve will therefore be quite safe as long as oscillations are taking place, and just safe when they stop. This example is typical of the earliest naval power valves. As the proportion of I_e to I_o is made to exceed that given, the valve will become less and less safe when oscillating. However, a valve designed to work in a modern high-efficiency transmitting circuit of efficiency η would have the ratio I_o/I_e of the order of $(1-\eta)/2$, and a 250-watt valve such as that here considered would be given a saturation current considerably greater than 0·34 ampere.

We have first to select a suitable filament temperature. This will be done from consideration of the working life required. Suppose that this is to be long, over 1,000 hours, and that previous experience, as is actually the case, indicates 2,310° K. on Stead's scale as suitable for ensuring this. We now proceed to find the length of an ideal filament which is fully hot right up to the ends. Allowing a margin on the 20-volt supply, we take the filament voltage to be 18·2 volts. From Stead's curves the values of E_f' and I_e' at 2,310° K. are found to be 0·165 and 0·91 respectively.

Now
$$l_f^{3/2} = \frac{E_f}{E_f'}\sqrt{\left(\frac{I_e}{I_e'}\right)}$$

whence we obtain 16·5 cm. as the length of the filament which when arranged in a single hair-pin loop will give a filament system of axial length 8·25 cm.

The length of the anode to be bombarded by such a filament should preferably be somewhat less, for instance, 6·5 cm. This with a diameter of 3·2 cm. will mean at 250 watts a radiation as low as 3·2 watts per square cm. even without allowance for radiation from the open ends, which is little more than one-half the limiting value found for nickel.

In this example we will take a grid diameter of 1·0 cm., which, though practicable, represents the limit of narrowness for use with so long a filament loop; something nearer 2 cm. would now be more usual.

In the anode-current formula all quantities except m are now known. Transposing the formula we have

$$(m + 1)^{3/2} = \frac{2{\cdot}12 \times 10^{-5} l_f'}{d' I_e} E^{3/2}$$

the value of m calculated from which is 12·0. Applying a deduction from this required value of m to allow for longitudinal supports to the grid, we find that a value of m of about 12 will be given by a helical grid having 4·6 turns per cm. of 0·02 cm. diameter wire, with three longitudinal supports 0·06 cm. in diameter.

The ideal filament used up to this point has now to be replaced by one in which proper allowance is made for the cooling of its ends. This is done using Stead's methods and data, and the resulting length of wire in the filament is found to be 17·6 cm. and its working voltage 18·2 volts. At the same time its diameter is 0·0023 cm. and the working current 5·4 amperes.

It may be of interest to add that the anode-current grid-voltage slope for this valve at 0·17 ampere anode current is given by

$$k_1 = \frac{3}{2} \times \frac{I_o}{E} m$$

and has the value 2·0 milliamperes per volt.

This example gives a valve having good margins of safety in all respects except the clearance between grid and filament. This, however, could readily be increased with the sole effects of slight reductions in the values of m and k_1.

If, however, a filament temperature 150 degrees higher had been taken, the filament supply would have been reduced to 3·6 amperes at 10·8 volts, but its life would have been much shorter, about 300 hours only. The whole construction would have been more compact, the anode being only one-half the size, and the valve generally closely similar to the T2B valve designed for the Royal Naval Air Service. This, owing to the high temperature reached by the small anode, and the small size of the bulb, is more difficult in manufacture and less safe in operation. It shows great economy in filament power and in space, but represents approximately the limit in these directions for a valve of this power.

It will be noted that the power at which the valve is rated is that which can safely be expended in it, not that which it will control, this latter being dependent on the efficiency of the circuit arrangements as well as on the valve.

This network of interlocking formulæ, together with the appropriate numerical data for tungsten, made it possible to calculate essential dimensions for all the electrodes of various experimental valves designed to meet anticipated needs. These designs, and suggested procedure for the exhaust of the valves, were discussed with several lamp-manufacturing firms in the first weeks of 1917. Very shortly afterwards it became apparent that the problem had been taken up by Mr. F. P. Driver of the Osram-Robertson lamp works and his staff with notable energy and persistence. The results of these efforts constitute a model of industrial research.

The start was made with a material equipment which included nothing out of the ordinary. The pump was the Gaede mercury pump, a rotary pump working by displacement, and slow at high vacua. In the latter stages of the exhaust this was therefore supplemented by a large charcoal tube immersed in liquid air. This would condense the residual gases very completely, but only provided the quantity did not exceed the limited absorbing capacity of the charcoal. The combination is not to be compared as regards either speed or effectiveness of working with the rotary and other molecular pumps in use at the time in America. However, in this case it proved enough for success; improvement came later.

The essential dimensions of the electrodes being stated from the calculations, the method of attachment and mounting was left entirely to the works. The processes of cleaning the metal parts before exhaust and of heating the glass were those which all lamp manufacturers recognize to be necessary for metal-

filament lamps; the construction of the metal work recalls the half-watt lamp in some details, but was mainly original.

It did not take long for a form to be produced which was sufficiently nearly perfect to persist with none but minor alterations through a number of subsequent designs. The T1 valve (Fig. 9) was one of the first to be manufactured in quantity. Its evolution, though short in point of time, was a very active process. The number of the unfit which perished before survival was achieved was surprising. A contemporary of the first half-dozen survivors, of whose fitness there was incidentally little question, has been lent by the makers. It dates from a time only five or six weeks subsequent to the communication of the designs. The kind of performance of which these early specimens were capable is indicated by the case of the pair which were in regular and very frequent use in the Fleet flagship for over a year.

In these valves, that is to say in those following the very first, it was found necessary to make an empirical correction to the electron data to allow for differences between English and American tungsten. This correction served until the data were redetermined by Stead as described in a recent communication to the Institution.* Otherwise comparison between the observed and calculated characteristics in the neighbourhood of the working adjustments showed agreement to within less than 10 per cent.

The T4A valve (Fig. 10), a later design, is rated at 400 watts and is therefore capable of converting over one kilowatt of input power in a circuit of good efficiency.

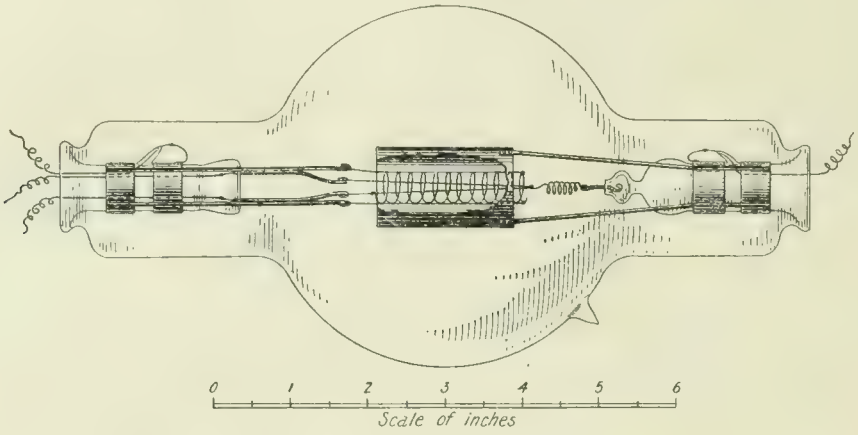


FIG. 9.—Transmitting valve, type T1.

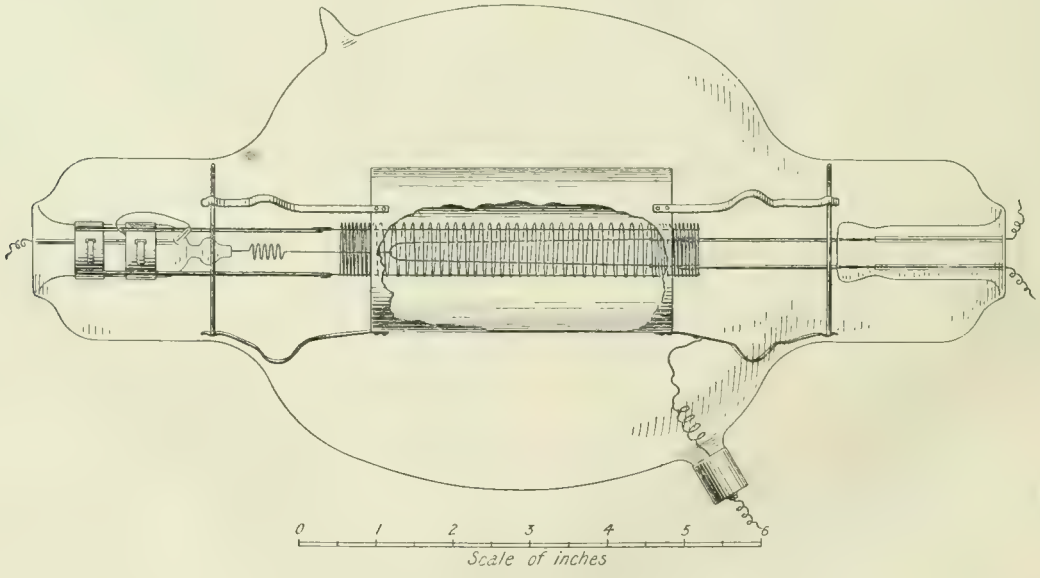


FIG. 10.—Transmitting valve, type T4A.

* *Journal I.E.E.*, 1920, vol. 58, p. 107.

Several essential points to be observed in manufacture were established at an early stage.

The high vacuum was found to be permanent, provided that the power expended in heating the anode, and indirectly the other metal work in the valve, during the final stages of the exhaust was considerably greater than that expended under the most severe conditions permitted in working. This was the basis of the system of rating the valves by the maximum power which could be expended at the anode for a definite period, 10 minutes. It was necessary, therefore, to have the anode large enough to leave a margin between the rated power and the power required to melt the nickel anodes fitted.

Uniform heating of the anode was found to be necessary if the vacuum was to be permanent, and for this

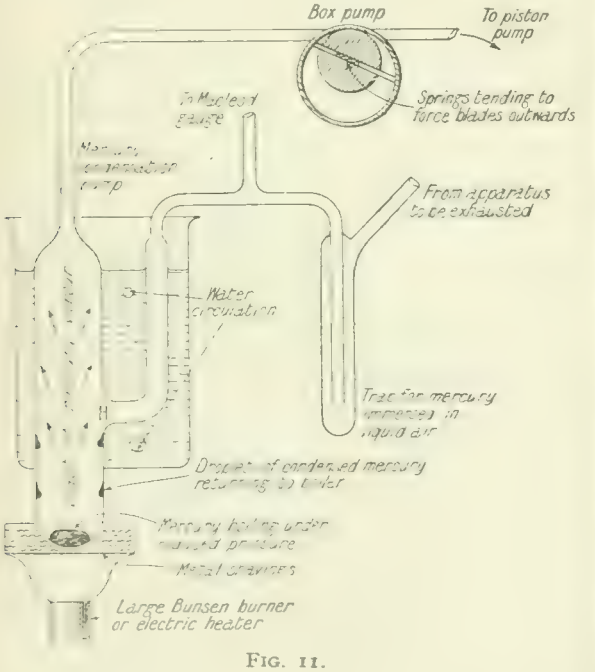

Box pump
To piston pump
To McLeod gauge
Springs tending to force blades outwards
From apparatus to be exhausted
Water circulation
Trap for mercury immersed in liquid air
Drops of condensed mercury returning to boiler
Large Bunsen burner or electric heater

FIG. 11.

reason it is desirable that the filament be at least not shorter than the anode.

For a similar reason grids having a large number of small spaces separated by fine wires were found preferable to those with thick wires and correspondingly large spaces, the discharge through which caused local overheating of the parts of the anode immediately opposite.

Extreme rapidity of pumping up to the last stages of the exhaust was found to be essential, and there was a great improvement on substituting for the combination of Gaede rotary mercury pump followed up by charcoal in liquid air as at first used, the mercury-vapour condensation pump, the first of which to be used was lent by Professor Sir J. J. Thomson in the spring of 1917.

This pump is shown diagrammatically in Fig. 11. It works by a kind of ejector action, the velocity of the dense blast of mercury vapour up the central space past the side aperture H being great enough to prevent completely all possibility of any gas molecules leaving H in the ordinary course of diffusion ever returning.

The tube immersed in liquid air prevents diffusion of mercury vapour back to the valve and also condenses much of the evolved gas. It is not, however, essential, particularly when small valves are being exhausted.

On the lower vacuum side of the vapour pump comes a box pump, the chamber of which is divided into two halves by a pair of spring blades which rotate eccentrically pushing the air before them, the rubbing surfaces being kept gas-tight by a liberal supply of oil. Beyond this again is a piston pump.

It was observed that when an alternating voltage was applied between anode and filament the valve conducted both ways as long as any blue glow (indicating the presence of positive ions derived from gas) was present. If the glow was allowed to become very bright the mean current through the valve might even reverse, implying that the conductivity was higher when the filament was positive than when it was negative. As might be expected under these circumstances, the valve still conducted momentarily after the filament current was switched off.

Overheating of the filament seals owing to conduction of heat back from the filament led to electrochemical decomposition of the glass, indicated by a black deposit on the platinum in the seal, and consequent leaks. The combination of heat and high-frequency electric strain caused breakdown of the glass between the filament and grid seals as soon as the oscillatory voltage in the grid circuit became high. This was, however, easily prevented by separating the seals.

The first power-rectifying valve U_1 was produced by simply omitting the grid of T_1 and gave no trouble. Another, U_2, which was equally successful, was designed by Lieutenant Sleeman to suit a particular set of circuit requirements.*

This description of its early stages covers practically the whole of the relatively uneventful history of power valve development. The manufacture proceeded by dozens, and then by hundreds, reaching a total of some 5,000 in the period considered. Six principal types of power valves were finally in use.

(6) The Development of a High Vacuum Receiving Valve.

At the end of 1916, the difficulty of reproducing soft valves of the audion type was becoming serious, and Round's "Q" valve, in spite of the high voltage it required to produce fair characteristics (Fig. 12), was used in an ultraudion receiver designed at this time.

The British Thomson-Houston Company, having made progress with a method of producing high-vacuum valves of the French pattern for the Royal Naval Air Service in particular, suggested an attempt at developing a high-vacuum substitute for the audion on similar lines. It was known that the French valve itself would not produce the heterodyne oscillations over the full range of wave-lengths required of the

* Fortescue: *Proceedings of the Physical Society*, 1919, vol. 31, p. 319

receivers for which valves had to be found, but various sets of modified trial valves were made up and by accident one of these specimens provided a solution of the problem in an unexpected way. In all the trials the grids had been made too open, the full importance of keeping down the slope of the anode-current/anode-voltage characteristic not being realized, owing to the complication of the modified ultraudion circuit in use. However, in one specimen valve a warping of the filament brought grid and filament so very close together that the effective closeness of the grid was more than doubled, the variation of anode current with anode voltage was much reduced, but the corresponding variation with grid voltage was unaltered. This freak valve did all that was required, but was not itself reproducible. However, a further trial valve was designed using what had been learnt from the power valves as to the general effects of the different dimensions of the electrodes, and it was found possible to reproduce the desired characteristics sufficiently closely, using a symmetrical and readily reproducible form of construction.

The new valve had the same filament as Mr. Edmundsen of the B.T.H. Company had fitted in the experimental one, but had the other electrodes cylindrical. The grid diameter was made as small as possible, as this, together with the length of the filament, which was

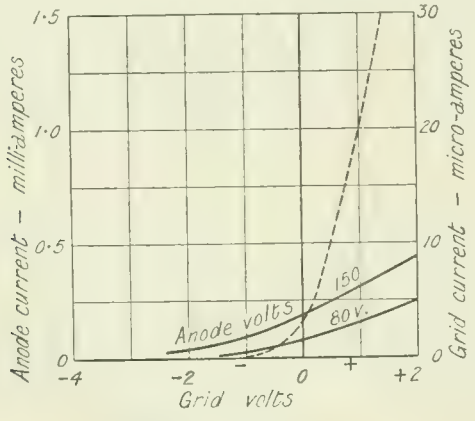


Fig. 12.—"Q" valve.

greater than in the French valve, were now known to be factors in determining the slopes of the characteristics. The diameter and spacing of the grid helix were chosen so that the calculated value of the grid constant m should be the same as had been observed in the freak valve. As the double-ended audion construction was now replaced by the French method of mounting all the electrodes on a single stem, so that they could be finally adjusted before sealing into the bulb, Mr. Edmundsen brought the filament leads round the outside of the bulb to a screw cap secured to the sealing-off point.

This valve, known as R4, met practically all requirements for a year or more, ousting the soft valves giving the audion characteristics in most cases where they were issued as an alternative. It was sufficiently similar to the soft valve to give comparable results for most purposes; but for various reasons it turned out to be more reliable than any soft valve in existence at the time of its appearance. This would tend very much in its favour, for a small gain in reliability is felt far more by the receiving operator who passively waits for and takes in the signal than by the transmitter who makes it on his own initiative. The most serious form of unreliability, sudden failure of the filament, proved to be very rare in this valve, the dimensions given to the filament providing in the first place that it could not be overloaded to the fusing point in a 4-volt, or even in a 6-volt circuit, and, further, giving to all filaments not locally damaged in exhaust or strained too tightly an expectation of life which was excellent, indeed, almost excessive. More than one R4 valve on

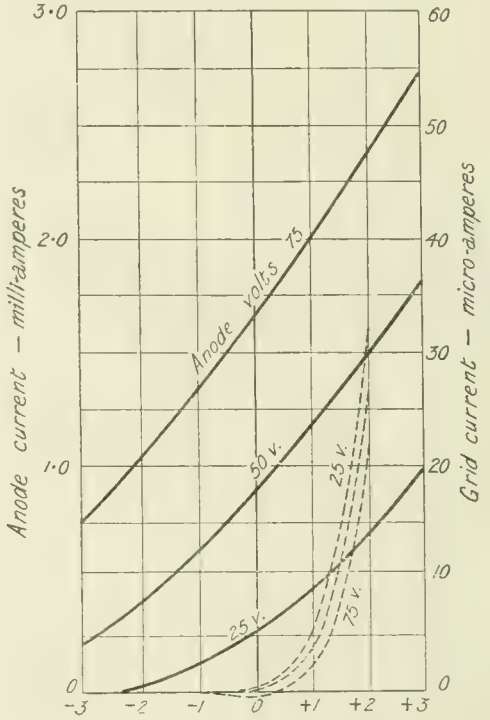


Fig. 13.—"R4" valve.

life-test survived 8,000 hours (i.e. 12 months) of continuous burning. The life on service may have been shorter, but apparently several thousand hours was the rule. Such a life was a great advantage to isolated ships, and the corresponding small rate of consumption of valves in the receivers in use made it easier to build up stocks in the dockyards for the use of more accessible vessels, and for new ships.

The characteristics were good. As shown in Fig. 13, the slopes at an anode voltage of 50 are comparable with those of the French or the hard audion valves at 70 or 80 volts (Fig. 14), while the corresponding anode current was less in the proportion of three to one. The low anode voltage, besides reducing the number of cells in the anode battery, made possible the use of a much less severe exhaust, for at the lower anode voltage the effects on the characteristics of traces of residual

gas are much less marked. This imperfect exhaust, again, was later found to steady the emission of electrons from the thoriated tungsten filament fitted.

Some of these virtues, however, were latent for a time. Although a life of 1,500 hours had been shown to be possible by life-tests conducted at the National Physical Laboratory on high-vacuum audions, and was attained by the first delivery of the R4 valves, it was soon found that the process developed by the B.T.H. Company for exhausting French valves for other services would require modification if such a life was to be ensured. The makers were not prepared to make modifications at the time, but preferred to concentrate on the French valve. Other sources of supply were therefore sought.

After some work at Cambridge on the emitting properties of the filament, and on the proportion of

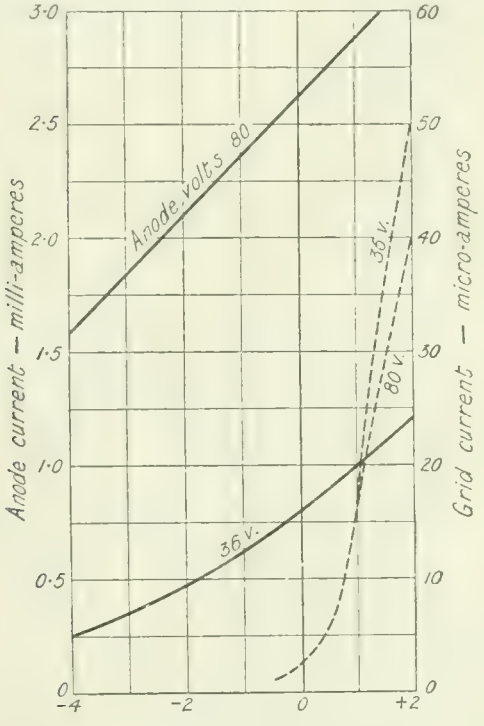


FIG. 14.—French valve.

grid to anode current, a specification was drawn up and other lamp makers called in. The specification was a simple one, the electrical tests covering first a saturated emission current some five times the normal anode current, to be attained with a filament voltage not exceeding the 4 volts of the supply accumulators, and current within the range of the 1·2-ampere instrument fitted, and together with this a vacuum test permitting a reverse grid current of 2 micro-amperes with 100 volts at the anode. This corresponds to a positive ionization current of an order as high as 1/1000th of the primary electron current. The dimensions of the cold electrodes were given but the method of mounting was left optional.

In the subsequent development of the manufacture the Osram-Robertson Company, using the experience acquired with the power valves and soft receiving valves, made the most rapid progress. From observations on the rapid disappearance of gas from some of their soft valves on life test, it had been hoped that high-tension bombardment of the anode and consequent damage to the filament could be dispensed with. It is now known, indeed, from recently published accounts that many German receiving valves were exhausted on such lines. However, in this case the method was found to be too sensitive to variations in the quality of the materials used, and the process finally developed in conjunction with the Osram works employed the minimum bombardment which would give a permanent vacuum and so damage the filaments as little as possible.

In arriving at this minimum, much information was obtained as to the way in which the high vacuum in valves is maintained.

If the bombardment is severe and the exhaust thorough, the high vacuum is permanent and no softening occurs until the electrodes are overheated, as might occur in transmitting valves.

With reduced bombardment there is a tendency to a slow continuous evolution of gas during working, favoured by a high filament temperature. Counteracting this, however, there is a continuous absorption or "clean-up" of gas taking place at a rate dependent on the largest potential difference applied between any of the electrodes. The origin and ultimate destination of the gases is obscure, though the "clean-up" effect is a well-known one, occurring in lamps, and also at much higher voltages in X-ray bulbs.

Thus, for each particular value of the working anode voltage these two actions strike a different balance; the higher the voltage the lower is the equilibrium pressure and the better the vacuum. Equilibrium is not instantaneously obtained or disturbed. In the case of R4 valves running continuously with the filament at normal brilliancy (3·5 to 4·0 volts) the vacuum deteriorates at first, the valves softening rapidly for the first two or three hours. After this, provided they have not reached a state corresponding roughly to the softness of an R2 valve, i.e. a reverse grid current of 1 micro-ampere with only 30 volts applied to the anode, a progressive hardening begins and continues, if the exhaust was carried sufficiently far, until the vacuum is much better than that specified as the limit for R4, and often also much better than immediately after the removal of the valve from the pump. Trials at the Royal Naval College, Greenwich, established that a considerable amount of gas is given off when the glass of the outlet tube is heated for sealing-off. If the sealing is too rapidly done much of this gas is left in the sealed valve.

The definite nature of these effects being established by many trials, it was decided that the process of "ageing" by running the valves at the works for a few hours between exhaustion and test was preferable to over-bombardment, as the filament was saved and it was also ensured that each valve had before test and issue a preliminary run under working conditions, so that greater reliance could be placed in its constancy.

In the course of these trials many opportunities occurred of observing the connection between the amount of gas present in a given valve and the emissive power of the filament for electrons. It was clearly established

that the greater the amount of gas the greater the watts expended in heating the filament and therefore the higher the filament temperature required to produce a given total electron current, the effect continuing down to gas pressures far below those required to produce any appreciable cooling of the filament such as can be detected in gas-filled valves. This effect is also a slow one, and if it is pronounced the emission current may take several minutes to attain a steady value after the working conditions have been changed. This is one probable reason for the lack of reliability of the early "audion" valves. The effect is favoured to some extent by a low filament temperature, but more markedly by the application of voltages above 25 or 30 volts to either or both of the cold electrodes. It is thus probably a case of the electro-chemical contamination of the surface of the tungsten by the gas ions as investigated and described by Langmuir (*Physical Review*, 1913, vol. 2, p. 450). If present, it makes any true estimate of the form of the "saturation" portion of the characteristics difficult to obtain, the values of the currents at or near the saturation value tending to be too low unless taken by some instantaneous method.

A kind of inverse of this effect, that is to say the occurrence of cases where the filament watts for a given total electron emission were abnormally low, was investigated at the Royal Naval College, Greenwich, and shown to be associated with the presence of impurities derived from the body of the filament, and especially with the presence of thoria added to the tungsten ore to improve the mechanical properties of the wire. As it is observed to occur whenever the bombardment of the filament by positive ions, especially those derived from volatile metals present as impurities in the electrodes, is more than ordinarily violent, it is supposed to arise from the exposure of thoria or of thorium-tungsten alloy by the disintegration of the filament surface, and therefore practically from the substitution of another emitting material for the pure tungsten. The effect is fairly permanent and may under certain conditions persist during several hundred hours of running.

During the development of the R4 valve, it was established that any over-straining of the filaments with the object of preserving accurate centering resulted in a very troublesome defect. Under such conditions a filament, although to all tests perfect and undamaged, would fail suddenly after less than 10 hours' normal running under conditions where a life of many hundreds of hours was to be expected. Various methods of spiralling or waving the filament wire may be used to prevent this effect, but without them a very little warping of the supports during exhaust is likely to bring it on in a considerable proportion of the valves.

Some preliminary experiments were carried out which confirmed that it was desirable to make the grid of the R4 valve consist of a number of turns of fine wire rather than fewer turns of thick. There are theoretical grounds for supposing that the proportion of the electrons leaving the filament which the grid does not succeed in deflecting as they pass—in a cylindrical valve it does not begin to attract them until its potential is nearly the same as that of the anode—depends amongst other factors on the extent to which the grid wires block the "field of view" from the filament. This may be measured by the area of the grid "projected" on to the anode.

Experiments were carried out on the effect of different grids on the ratio of the anode and grid currents. Three valves were used, each fitted with a different type of grid. These grids all had the same effective closeness (i.e. the same de/de' or m defined as previously described), but were made of wires of different diameters, their projected areas differing in the extreme cases in the proportion of two to one. The valves were exhausted as completely as possible by means of a Gaede pump, followed up by liquid air and charcoal, and curves were then drawn for each valve showing how the ratio of grid current to anode current varied with grid and anode voltages. The curves are of the general form shown in Fig. 15. The anode and grid voltages

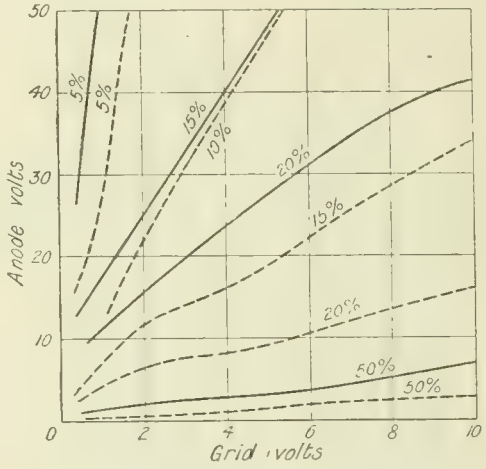


FIG. 15.—Curves showing the voltage adjustments for given ratios of grid current to anode current.

Full lines are for coarse grid, 0·04 cm. wire and 5·5 turns per cm.
Broken lines are for fine grid, 0·01 cm. wire and 12 turns per cm.

are plotted along the two axes, and each curve is a line along which the grid current is some constant percentage of the anode current.

It was found that, for a given anode and grid voltage, the valve with the largest projected grid area showed the largest percentage grid current, as might be expected. Further, for the region in which the form of the curves could be predicted theoretically (i.e. the region where the grid voltage is positive, and fairly large, but considerably smaller than the anode voltage) it was found that the agreement between theory* and experiment was good.

The proportion of grid current to anode current throughout the range of working adjustments can therefore be reduced without affecting the screening effect of the grid, measured by the value of m, simply by making the grid of a larger number of finer wires. This reduces the mechanical strength of the grid, which can, however, be restored by making a mesh of the fine wires, this naturally being much stiffer than a helix.

As far as the effect of the form of the grid is concerned, the numerical investigation of grid currents has not been carried further than this.

* Due to Sir J. J. Thomson and extended by Lieut. Brundrett.

For receiving valves there is another factor of great importance controlling the form of the lower part of the grid-current/grid-voltage curve, the part used when rectification takes place at the grid. This part is, in all high vacuum valves below the point where the traces of gas cause reversal of the grid current, of a form such that if successive equal changes of the grid voltage are made in the positive direction, the value of the grid current is multiplied each time by the same amount, the curve being therefore an exponential one. The reason for this is that, although the electrons do not all leave the filament with the same velocity, there is, nevertheless, a very definite law connecting the proportion having one velocity and the proportion having another, that is the numbers which will overcome different degrees of repulsion by the grid consequent on different voltages being applied to it. This law was established by O. W. Richardson. It is found that the observed factor of multiplication for the lower part of both curves, grid and anode—in round numbers twice for every fifth of a volt—agrees very closely with that to be expected from the law of the distribution of initial velocities.

As long as a heated surface is used as the source of the electrons, this variation in initial velocity and therefore the general form of the characteristics up to about the 20 micro-ampere point is uncontrollable by any simple means.

The form of the grid curve is thus determined by the exponential law, and its vertical scale by the projected area of the grid. It is also observed that a change in the nature of the surface from which the electrons are emitted may result in the curve being shifted bodily by as much as 1 volt. Thus, these thoriated filaments which give an abnormally large electron emission for a given temperature give rise to a grid curve displaced by anything up to 1 volt in the negative direction, i.e. to grid currents up to 70 times as great for a given grid voltage.

"Soft" and Gas-filled Valves, Properties and Development.

If the quantity of gas in a valve is not extremely minute its presence gives rise to certain special modifications, both in the characteristics of the value and in its behaviour in use. Owing to their many common properties such valves are often classed together and spoken of as "soft" valves, the name being taken from X-ray tubes in a similar state. The softer a valve is, the more gas it will in general contain, and, correspondingly, the harder it is the more nearly perfect will be the vacuum within it.

A more coherent explanation of the special properties of soft valves can perhaps be given if they are treated as variants on the high-vacuum valve which, though a later development, is now more generally understood, having come into far greater prominence, both in practical use and in the literature of the subject. In dealing with soft valves, therefore, departures will be made from the roughly historical treatment followed in the rest of this paper.

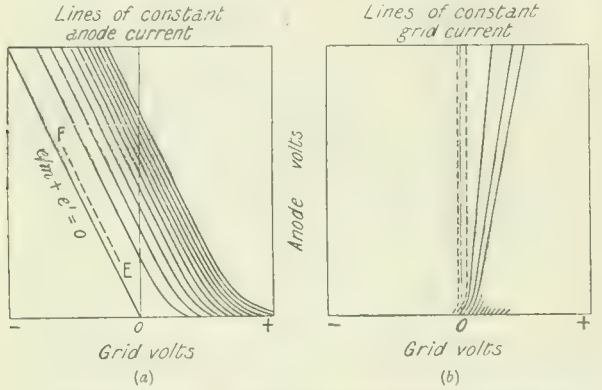
The chief point of distinction is that in the soft valve as soon as the potential difference between filament and anode, or between filament and grid, exceeds a certain value characteristic of the gas present, positive ions arising from the disruption of gas molecules appear near the high potential electrode. These ions are directed by the electric field towards the neighbourhood of the filament, where their presence tends to cause a neutralization of the dense space-charge in that region due to the negative electrons from the filament. Under working conditions the neutralization is usually only partial, and the result is simply that the applied field tending to draw the electrons away from the filament has less space-charge to contend with and, consequently, is competent to produce a larger electron current than if no positives were there. As the positive ions owe their origin to the collision of electrons with gas molecules, such adjustments of the voltages as produce no space-current in a high-vacuum will produce none when the gas is present. As regards the position of its foot, therefore, the characteristic curve will be unaltered, but as one follows the curve it will sooner or later be found to depart from the form which it would have in the high-vacuum case. Take, for instance, the curve connecting anode current and grid voltage, for an anode voltage of about 30. This will become steeper and steeper, and, unless either the effect of the gas is small or the saturation value of the current low, a point of discontinuity of the curve will be reached corresponding to an instantaneous rise of the current to a value several times at least larger than that immediately preceding, and often reaching the full saturation value at one leap. If after passing the point of discontinuity the potential is reduced again, the former characteristic is not usually retraced, but the high value of the current persists and the point of discontinuity comes at a lower potential than the corresponding discontinuous rise. This is sometimes spoken of as a "hysteresis" effect, and its appearance renders the valve either inactive or very difficult to adjust.

The possibility of this effect, which might easily escape the notice of an operator, was a source of much trouble in the earlier soft valves. We shall return to it in connection with the steps by means of which it was eliminated. The essential properties distinguishing a less pronouncedly soft valve are, however, more regular and more capable of prediction than this, and in general considerably extend the possibilities of a particular arrangement of electrodes. In a triode valve the appearance of the positives results merely in a more or less marked increase in the anode current, owing to the partial neutralization of the space-charge. The effect on the grid current is, however, less simple. If the grid is the most negative by one or two volts of the three electrodes, no electrons can reach it, but, on the other hand, a considerable proportion of the positives are arrested by the grid, either in transit towards the filament, or after missing it owing to the small target which it presents. This influx of positives produces a grid current in the reverse direction to that observed when the grid is picking up electrons. If now the potential of the grid is changed in the positive direction until it repels the electrons less completely, so that in the high-vacuum case it would pick up an appreciable number of them, this number may be increased by the

presence of the positives, somewhat in the same proportion as the total number of electrons escaping from the filament is increased. If the grid is made sufficiently positive to the filament, this effect may mask the picking up of positives and the direction of the current may become the same as in the high vacuum.

These effects are well illustrated by means of a particular method of plotting the characteristics, the use of which had some value in throwing light on the physical actions described as underlying the modifications of the currents observed to occur when gas was present.

Instead of plotting to a horizontal axis of grid voltage with a vertical axis of current, make both axes represent voltage, the horizontal for the grid, and the vertical for the anode. The various values of the current have then to be indicated by means of lines of constant current, like the isothermals on an indicator diagram or the contour lines on a map. The characteristics indeed take the form of a contour map of a surface of which the more usual curves of current against grid voltage are sections in vertical planes. When, therefore, the difference in current between successive lines



FIGS. 16 (*a*) and (*b*).—General characteristics of high-vacuum valve.

is large, or the distance between them small, a steep slope of the sectional characteristic is indicated. It is generally as well to show the grid current and the anode current on separate diagrams. Intersecting curves, which cause some confusion in sectional characteristics of soft valves, are thus entirely avoided. Further, as the successive intervals of current can be selected at will, it is possible by using small intervals where the currents are small, and increasing the intervals more or less in proportion to the currents, to give an equally faithful rendering of all parts of the surface. This is particularly useful, for it is generally necessary to trace the variations of a current from a fraction of a micro-ampere to 10 milliamperes or more.

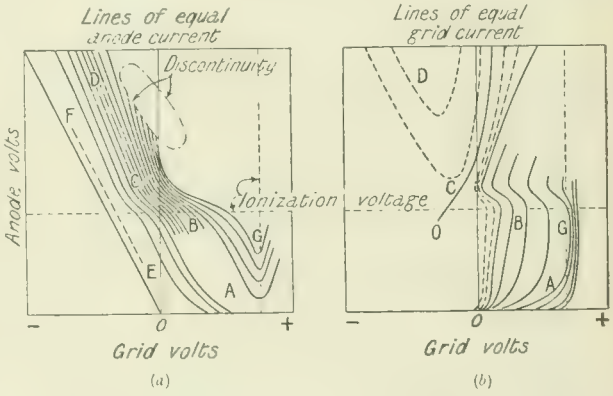
In the case of the high-vacuum valve both surfaces depicted in this manner are simple, that of anode current particularly so, Figs. 16 (*a*) and 16 (*b*). For all the region where the grid current is much the smaller of the two, that is, for all but the right-hand bottom corner of the diagram, the lines of constant anode current are nearly straight and nearly parallel. Now the inclination of the lines to the horizontal—measured as a slope of n to 1—is the measure of the effective value of the grid or amplification factor m at the point considered. Their straightness and parallelism is therefore a very clear and striking expression of the fact already mentioned, that in this region m is sensibly independent of the value of either grid or anode voltage, and that the current is a function of $e/m + e'$.

As would be expected also, the anode current becomes vanishingly small to the left of the line $e/m + e' = 0$, the crossing of which implies the reversal of the field at the surface of the filament.

The lines of grid current, also, as long as the current is small, are straight and parallel to the axis of anode voltage, the grid current being then independent of the anode voltage. For larger values of the current they approximate to radial lines spreading out from the origin.

If secondary emission of electrons from either of the cold electrodes occurs, as for " dynatron " adjustments, the surfaces illustrate the progress of the effect very clearly but become rather complicated.

The general differences between the characteristics drawn in this way, for high-vacuum and for gas-filled



FIGS. 17 (*a*) and 17 (*b*).—General characteristics of soft valve.
Minute currents are shown by broken lines.

valves is illustrated by comparison of Figs. 16 and 17. The soft valve is clearly not so simple as the hard, but it is noteworthy that up to the point B there is little difference between a valve with the highest vacuum and one which is filled with gas to the maximum practicable extent. At A on the diagrams, where most of the current is going to the grid, the anode current varies little with the grid voltage, rather more between A and B, but very little again beyond B. B is a point at which the gas begins to ionize. The ionization, which is consequent on the anode voltage exceeding the ionization value, causes a large increase of both anode and grid current, and so both sets of current contours swing off sharply to the left, the horizontal direction of the lines indicating that the valve is in this region much more sensitive to the value of the anode voltage than to that of the grid voltage.

The curve marked O on the grid-current diagram is the line of zero grid current, whilst the curves to the left of this near the point C represent reverse grid currents or " backlash." The curve E F is drawn for a very small anode current (e.g. 10 micro-amperes). It is a nearly straight line, and the slope of the lower part of

it is of importance, as it gives a close approximation to the value of m for high-vacuum conditions. It is only the lower contours like E F, that can be used thus for measuring the effective closeness of the grid fitted, the others such A B, C D, are profoundly modified by the presence of gas.

Extending the diagram in the direction of increasing positive grid voltage, until the grid voltage exceeds the ionization value, the grid current is found to rise very steeply, and there appears in the anode surface a bulge or shoulder G, followed by a hollow indicating a reversal of the anode current, just as previously described for the grid current at high anode voltages. That the functions of the two electrodes should be thus interchanged even in the soft valve, simply by making a suitable transposition of their voltage adjustments, is remarkable, and provides, when all parts of the complete surfaces are passed in review, a great variety of combinations of characteristic slopes, very few of which have as yet been utilized in practice.

This conception of the generalized characteristics of the soft valve as distinct from the hard owed its full development to the study of an experimental valve sent by Professor F. Horton in October 1916. This valve was filled with helium which was and remained very pure, so that the valve was very steady, and the appearance of the ionization effects as either voltage attained the critical value of 21 volts was very sharply defined. Shortly afterwards similar observations were made on some experimental valves received from Professor O. W. Richardson. These, together with a re-plotting on the contour system of Stead's characteristics of valves with movable electrodes, both plane and cylindrical, all confirmed the general form of the soft valve characteristics shown in Figs. 17 (*a*) and (*b*).

Richardson's valves were exhausted for many hours in a vacuum furnace, and were beautiful instruments for experimental investigation. The ionizable atmosphere consisted of mercury vapour from a reservoir containing mercury. By enclosing the valve in an oven and suitably warming it, standard characteristics at any desired degree of softness could be obtained. It is interesting that when discontinuities began to occur as the valve was softened, they were limited at first to a small enclosed region just above the shoulder of the anode surface at C, disappearing again when the anode voltage was sufficiently raised. Richardson's series of valves of this kind completely bridged the gap between the audion and the Round valve, indicating that the general effects of the admission of gas were the same in both of them, but were essential in the close grid valves if reasonably steep characteristics were to be obtained.

Of all the combinations of characteristic slopes which a soft valve can give, those used in practice seem to have been confined to the area near the point C on the general diagram, which lies on the shoulder of the anode surface where the slope is steep, but the run of the contours has swung back almost to its original direction, bringing the factor m back to something approaching its value for the same valve with a high vacuum.

On the grid-current surface the corresponding area comes at the head of the hollow representing the reversal of the grid current due to the positive ions. Here the curvature in the direction of grid voltage is often particularly sharp, giving good rectification in circuits where a condenser is included in the grid connection to receive the rectified charge.

On the current-contour form of diagram simultaneous variations of grid and anode voltage, such as occur in practice in almost all circuits, can readily be followed.

The course of a cycle of voltage variation can be shown as a closed curve described on the surface. The successive intersections of this curve with the current contours indicate the current variations during the various parts of the cycle. For a valve which is generating oscillations of measured amplitude in a circuit the dimensions of all components of which are known, the form of the ellipse depicting the simultaneous voltage variations can be calculated by means of vector diagrams.

A mathematical theory of a soft triode valve idealized as regards the structure of the grid and filament, but showing how for any gas there would be an upper limit of the pressure, and voltage adjustments, at which indefinitely steep characteristics would be obtained, and showing further the relative behaviour of different gases in this respect, was communicated by Sir J. J. Thomson early in 1916. An extension of this showed that the more open the grid the lower would be the limiting pressure, and gave some approach to the observed form of the characteristic surface for anode current in the region of negative grid voltage, indicating, for instance, that the increase in velocity of the positive ions with increase in anode voltage would have the effect of increasing m above its high-vacuum value, as actually observed.

The general investigation of the characteristics and behaviour of soft valves had progressed almost to the extent covered by the preceding sections, when serious difficulties in the manufacture of audions began to be encountered by the B.T.H. Company early in 1917.

The audion suffers very much from discontinuities in its characteristics, and the point of discontinuity is particularly susceptible to change in the pressure or composition of the contained gas, the limiting quantity of which is in any case small with so open a grid. As the best working adjustment came only too close to the point where a general glow diffused throughout the bulb appeared, accompanied by a break in the characteristics, which made the valve either inactive or at least very erratic, such faults could be very troublesome, particularly to those who were not used to them or content with less sensitive adjustments.

The glow point, indeed, was at first actually used to indicate the degree of softness in manufacture, but proved an erratic and unsatisfactory guide, the performance of the test itself giving rise to changes of the nature and quantity of the gas sufficient to alter the properties of the valve.

A deliberate attempt at so modifying the design of the audion as to make its characteristics specifiable and reproducible was begun in the spring of 1917. The question of the glow point was dealt with first. In experimental soft cylindrical valves made by the B.T.H. Company it was found to be practically non-

existent. This makes it appear that the general glow is due to ionization along the tracks of electrons which travel from the filament to the anode by long paths outside the electrodes. The grid has no control over what occurs in these regions. The probability of such paths is greatly diminished by adopting a cylindrical construction for the electrodes, and it has been found possible by this means to use much higher gas pressure than before. To test this point further a special valve was constructed in which the anode consisted of a cylinder, one end being permanently closed and the other end capable of being closed when desired by means of a cup carried on a stem floating in mercury. Observations were made on this valve with the anode open and closed, and it was found that by closing the anode the general glow could be entirely eliminated and " kinks " in the characteristics avoided.

In other respects besides this matter of the glow-point manufacturing considerations were much in favour of the cylindrical construction as used in the

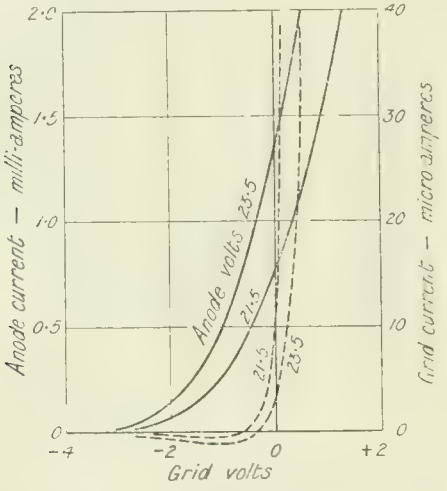


FIG. 18.—"R2" valve, filled with nitrogen at 0·1 mm. pressure.

French valve. In particular, this construction, like that of the ordinary incandescent lamp, allowed all adjustment of the electrodes to be made before they were put in the bulb, and involved no hand glass-blower's work.

The possibility of reproducing the audion characteristics with this construction had therefore now to be investigated. Four cylindrical valves were taken as a preliminary and characteristics were taken in a nitrogen atmosphere at pressures ranging from 0·018 mm. to 0·056 mm. These indicated that much higher pressures were practicable with these valves than with those of the audion type with flat anodes and zigzag grids. It was hoped that greater constancy would result from the presence of so much more gas, and trials of a substitute for the audion were decided upon.

Three cylindrical-type valves, with different grids, and two audion-type valves, also with different grids, were then sealed on to the pump and exhausted, and a long series of trials were carried out in nitrogen at various pressures. These trials involved tests of the working of the valves in circuits of the ultraudion type, the upper and lower limits of anode voltage for which the valves would produce oscillations being determined for a series of pressures between 0·0074 mm. and 0·6 mm. In most cases these oscillations were produced under difficult conditions with an inductance of 1,000 microhenries and a capacity of 0·005 mfd., together with an additional resistance of 2 ohms in the oscillating circuit, though other wave-lengths and other resistances were also tried.

Characteristics, e.g. Fig. 18, were drawn for the different valves and different pressures, for anode voltages chiefly in the neighbourhood of the upper and lower limits for which oscillations were possible.

The trials in the ultraudion detector circuit showed that a cylindrical valve with a thick wire grid was the most sensitive, and this construction has been adopted in valve No. R2, the grid of which is of 0·4 mm. wire in a spiral of 5·5 turns per cm. and mean diameter 4·5 mm. Full characteristics were therefore drawn for reference purposes for this type of valve, using a nitrogen atmosphere at various pressures between 0·0045 mm. and 0·5 mm.

As a result of these experiments a pressure of about 0·06 mm. was adopted for the nitrogen-filled R2 valves. It was a matter of great importance for the manufacturer of valves to be able to get an estimate of this pressure easily, before sealing off the valves from the pump. It was also highly desirable to have some method of estimating the pressure in a valve after it had been sealed off. The method which has been adopted for estimating the pressure in a valve while still on the pump was to have a special " vacuum tube " attached to the apparatus and measure the width of the " cathode dark space."

The electrodes of the tube were of aluminium, the cathode being a large disc. When a discharge from an induction coil is passed through the tube, there is a glow separated from the cathode by a dark space of sharply defined width. This width increases as the pressure diminishes, and also depends somewhat on the current density through the tube. The latter effect is sufficiently eliminated by using a tube of standard dimensions, and an induction coil of a definite size. Curves were drawn showing the connection between the pressure and the width of the dark space for nitrogen, hydrogen, helium, argon, and carbon monoxide. This was the method used in adjusting the gas pressure in the first 6,000 R2 valves containing mixed nitrogen and electrode gas.

In order to estimate the pressure in a closed valve, use has been made of the variation in the amount of " backlash " with the pressure. When the grid is one or two volts negative to the negative end of the filament, a reverse grid current is obtained as soon as the anode potential exceeds the ionization potential of the gas, and this increases as the anode potential is further increased, owing to the increase in the number of positive ions present. The anode voltage required to produce any particular backlash current increases as the pressure diminishes, and this is used to give an estimate of the pressure. For this purpose, curves were

drawn showing the relation between the pressure and the anode voltage required to give a backlash current of 1 micro-ampere, the grid being 1·5, 2·0 or 2·5 volts negative to the negative end of the filament. Curves of this kind are now available for nitrogen, hydrogen, helium, argon, and carbon monoxide. Fig. 19 shows the curves for pure helium and for helium contaminated by a considerable amount of electrode gas.

The dimensions of the electrodes, vacuum-tube tests, and a curve of pressure and reverse grid current were all embodied in an outline specification of the R2 valve, together with suggestions as to the method of exhaust, and were communicated to several lamp-making firms. As before in the case of the high-power transmitting valves, the Osram-Robertson works were the first to begin production in quantity, and from this point, June 1917, there was never any acute shortage of receiving valves for the naval sets in use.

The first nitrogen-filled R2 valves were found in practice to have one serious defect—the nitrogen gradually disappeared during the running of the valves,

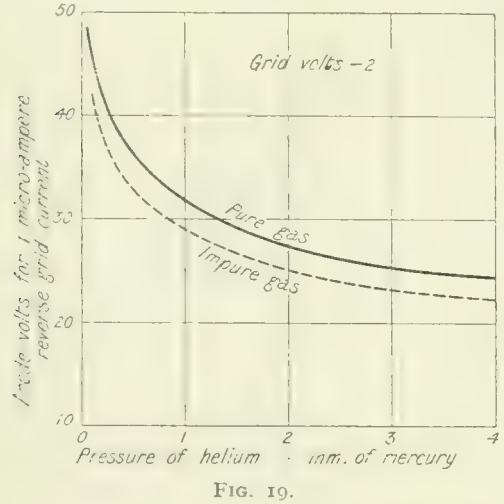


FIG. 19.

presumably being absorbed in the electrodes. For this reason it was thought that a chemically inert gas might be more satisfactory. Argon was first tried and experiments on oscillating points were carried out, thoroughly satisfactory results being obtained. Characteristics were also obtained for various pressures. It was found, however, that tungsten filaments disintegrated rapidly in an argon atmosphere, probably owing to the large mass of the positive ions, the life being so short that the use of this gas had to be abandoned.

Helium was next tried, for reasons which had gradually been coming to light.

Experiments had been carried out with an audion valve containing hydrogen at various pressures between 0·051 mm. and 0·0025 mm. and characteristic curves obtained. Similar experiments were made for a nitrogen atmosphere over a range of pressures from 0·038 mm. to 0·0005 mm. Special attention was paid to the small reverse grid current, often referred to as "backlash," obtained when the grid is made slightly negative to the negative end of the filament. The variation of the backlash current with the pressure and the nature of the gas was studied, and it was found that in nitrogen, and still more in hydrogen, the effect is much greater (at a given pressure) than in mercury vapour, which had been previously studied.

In a theoretical investigation of the "ideal" case communicated by Sir J. J. Thomson, it was shown that the characteristics of a valve in which gas was being ionized would become extremely steep whenever the product

$$\text{mass of positive ion from gas} \times (\text{current of positive ions})^2$$

became greater than the corresponding product

$$\text{mass of negative electron from filament} \times (\text{current of negative electrons})^2$$

This conclusion is confirmed by the results obtained with actual valves.

In hydrogen, where the positive ion is light, a large positive current is required. The presence of this is shown by the large "backlash" in hydrogen. To supply the ions for this current a correspondingly large quantity of gas is necessary, i.e. very much more of a light gas like hydrogen or helium is required to produce a given steepness of anode characteristic than of a heavy gas like mercury vapour.

This method of obtaining corresponding pressures was successfully applied to the purpose of obtaining from the known pressure of nitrogen a first estimate of the pressure of helium which would give a satisfactory R2 valve.

Now Horton's experimental valve with helium filling had shown the advantage of this gas in giving constancy of behaviour, and he had also used it in many other experimental valves both before and after the one we examined. Advantages on the theoretical side had, as described, become obvious in the meantime. His advice was therefore sought on the question of converting the R2 valve to a helium filling, in particular as regards the supply of gas, which turned out to be by no means so rare in the eyes of Messrs. Tyrer, from whom we obtained it, as we had imagined. He also refilled several R2 valves with helium at pressures indicated by the theory as corresponding to the pressure of nitrogen previously used; and these valves were found to be as constant as had been hoped throughout tests of several hundred hours' duration.

The experiments originally carried out for nitrogen, as described above, were repeated for helium. It was found to give most satisfactory results, and it was adopted in R2 valves in place of nitrogen. It is not absorbed by the electrodes, like nitrogen, nor does it cause disintegration of the filament, as in the case of argon. For a given pressure a helium valve is much harder than a nitrogen valve; in other words, a much higher pressure of helium must be used to obtain given characteristics than is required in the case of nitrogen. Roughly, the pressure of helium required is about 10 times the corresponding pressure of nitrogen. In R2 valves the pressure adopted for the helium is about 0·6 mm. As in the case of nitrogen, standard

characteristics, e.g. Fig. 20, at various measured pressures of helium between 0·05 and 4·0 mm. were examined.

Manufacture of helium-filled R2 valves was begun in September 1917, but owing to the same changes in the gas-content of the metal parts as had given trouble in the development of the R4 valve, they did not all behave as helium valves. In some the working anode voltage was lowered by contamination of the helium by more easily ionizable gases—one of the few difficulties special to helium. These valves had merely the same exhaust as a vacuum lamp, mechanical pumps only being used. All diffusion pumps and bombardment installations were at this time required for the supply of " R " valves to the Army, which was then, and for some months after, a pressing need. To expel the electrode gases the filaments were somewhat overburnt, and it was difficult to avoid shortening the lives by so doing. On the other hand it was necessary to expel enough gas for the valves to be constant. There were,

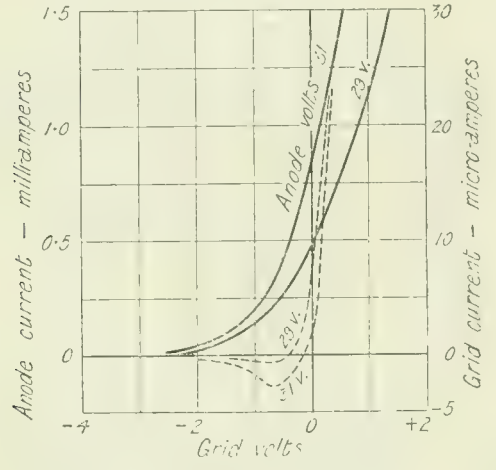


FIG. 20.—" R2 " valve, filled with helium at 0·6 mm. pressure.

however, many good valves giving lives of about 1,000 hours.

The final step of exhausting the valves as if they were to have a permanent high vacuum, and then admitting the helium, was not taken until about a year later. By this process, provided that precautions against the introduction of mercury vapour were observed, valves are obtained which are all as constant throughout their life as are high vacuum valves. Like them also, they differ amongst themselves somewhat, but to the same extent, and apparently for the same reasons.

Thus the reliable soft valve, the evolution of which began before that of the high-vacuum valve, and finished later, attained reasonable perfection and equally reasonable obsolescence at very nearly the same moment.

The soft valve, however, divides the honours of service actually done during the war in naval installations on equal terms with its high-vacuum rival, the R4, which ultimately accompanied it into obsolescence.

(8) Later Receiving Valves.

It was the extension of the use of valves to other receiving instruments besides the simple heterodyne that made the R4 valve obsolete. Multiple-valve amplifier sets were on trial for special purposes in 1917, and the properties of valves suitable for use in them were made the subject of general inquiry next after the power valves. The chief result of this work was to illustrate the difficulty of designing small valves. For instance, if the formulæ already given for power valves are applied to receiving valves, and further compact formulæ evolved embodying the essential properties of a valve for use, for example, in a resistance amplifier, the results are of far less practical value than had been found in the more fortunate previous case of the power valve, for the very good reason that the simple formulæ correspond to characteristics differing too widely from those actually observed in small valves. The discrepancy is due, in the first place, to doubt as to the effective length of the filament. Given the diameter of a filament the temperature of its central portion corresponding to a particular value of the heating current can readily be determined, and thence also the saturated electron emission per unit length of the filament in question. If now the length which would give the observed total emission is taken as the effective length, it is found that in filaments working at 4 volts or so the correction thus made amounts to a very large fraction of the total length of the actual filament.

Again, in most receiving valves the filament voltage is of the same order as the potential difference $e/m + e'$ between the negative end of the filament and the region of the grid. Hence it becomes necessary to know, not only the number of electrons which each small section of the filament is capable of emitting, but also its potential relative to the negative end in order to correct the value before assigned to the field tending to remove the electrons. For any exact knowledge of the effects responsible for the observed form of the characteristics of small valves, a previous determination of the distribution of temperature along the filament was required. Mr. Stead undertook, and very soon completed, an experimental investigation of this, adding a theoretical extension enabling the temperature distribution to be calculated for filaments of any dimensions. This work has already been fully described in a paper published in the *Journal* of this Institution.*

As a result, apart from the light thrown on the origins of the characteristics, it became possible to design alternative filaments without experimental trial, just as previously with alternative grids by the use of Sir J. J. Thomson's formula. For example, given the filament supply-voltage as determined by the accumulators fitted in an existing set, and the desired value of the saturation current, it became possible to calculate the dimensions of a whole series of alternatives ranging from cold, thick, and long filaments on the one side to short, thin and hot ones on the other. The members of such a series differ in heating current and in life.

* STEAD: *Journal I.E.E.*, 1920, vol. 58, p. 107.

Fig. 21 gives a set of curves so calculated for filaments all of which will give a saturated emission current of 80 milliamperes, and require a 6 volts supply for the heating current. The extent to which reduction of heating current has to be paid for by sacrifice of working life is here clearly shown. This series refers, it should be said, to the design of small transmitting valves. The Army B valve comes near the low-current end, and the results of the life tests were the basis of the design of the filaments of the R.A.F. F valve which comes near the middle, and of the naval T5 which, in order to obtain a longer life still, was given a current a little above the highest shown.

Similar series of receiving valves were worked out and tested, and a substitute for the R4 valve known as R4A having little more than one-half the filament current, and therefore better suited to double-valve sets were selected. In this case the diameter was actually selected so as to give a reasonable margin of

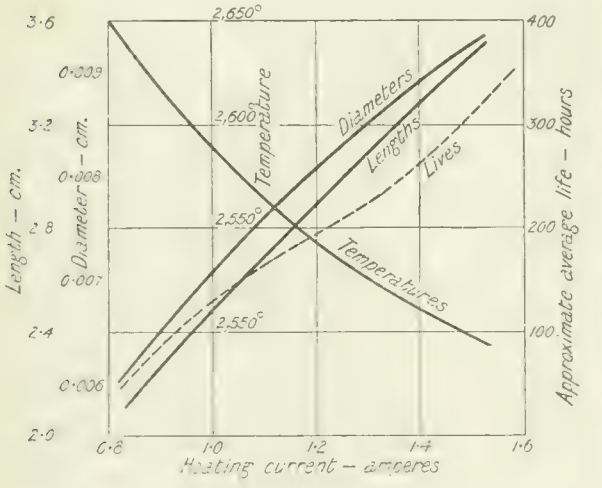


Fig. 21.—Alternative filaments, 6-volt supply, 80 m.a. emission.

mechanical strength, and the life obtained, some 1,500 hours, was still reasonably long.

During the life tests referred to, steady potentials approximating as closely as possible to those experienced by the valve under working conditions were applied, and the valves re-tested at intervals of one to seven days. The average life was determined from a batch of at least five valves, and the longest life was commonly observed to be about twice as long as the shortest. Many tests of this kind were carried out at the Signal School during 1917–18, involving a very large amount of careful work, the results of which were of the greatest value in setting a proper standard of reliability in working, and also making correct estimates of supplies required for naval purposes.

As in other similar cases the trials of cascade circuits of high amplifying power soon made conspicuous the existence of "valve noises" ascribable to rapid variation in the action of the valve. The deleterious effects of the presence of thoria in the "tungsten" filament were studied by Dr. Hodgson, Capt. Mullard, and Prof. G. B. Bryan in connection with the R valve at the end of 1917. Almost all filaments are noisy if the temperature is sufficiently raised. In the R4 the working temperature is so low that in many cases the crackling noise characteristic of thoria is absent although thoria was actually present. In the R4A, the reduced diameter was accompanied by a rise of temperature sufficient to make most R4A valves too noisy for use in amplifiers.

For some amplifiers a similar valve, called "R4B," was used having a filament of unalloyed tungsten. The R4B filament thus arrived at has practically the same dimensions as that of the original French valve, but is somewhat quieter in working, because the slightly smaller grid diameter makes the working anode current of the R4B distinctly the smaller. The saturation current, and therefore the filament temperature can thus be lower, and the noises are consequently reduced. The change from thoriated to pure tungsten made no appreciable difference to the working life. Evidently the temperature is not high enough for the special advantages of thoriated tungsten to appear. In all later receiving valves, therefore, pure tungsten was used, and it was found that silence was generally obtained up to a working temperature of 2,300° K. on Stead's scale, and with selected specimens of metal up to 2,600° K. The conditions for noise-testing were particularly severe, all extraneous disturbances, acoustic and electrical, being eliminated by most elaborate screening, and amplification of the order of at least three stages at audio frequency being employed.

During the early part of 1918 the trials of the various valves mentioned in the preceding paragraphs absorbed the available facilities for experimental work on small valves. It was, however, sufficiently clear that an amplifying valve should have a filament working below the noise point, and that its response to changes in the combined voltage, $e/m + e'$, should be as large as possible while keeping down the power expended in heating the filament, the anode voltage, and also, particularly where the anode circuit was to include a high resistance, the anode current. A further attempt was therefore made at selecting, on theoretical grounds, a combination of electrode dimensions so as to obtain some approach to an optimum in respect of these essentials.

In order to trace the several effects of the different factors, the theory was idealized to a considerable extent, the stage of approximation corresponding to curve 4 in Fig. 22, as described later. It became clear that the distance between grid and filament was the chief controlling factor, and that no very marked improvement on existing valves was therefore likely, though some reduction in the various currents and voltages was possible without spoiling the characteristics.

The results when valves came to be made up were somewhat disappointing, and showed that such experimental confirmation of the theory as had been available was spurious as regards the average valve, being based on freak observations such as are usually obtained in a small proportion of cases, as explained later in connection with the standardization of small valves. That the optimum was not reached at the first attempt was only

too clear, for the characteristics obtained were not so good as those of Round's "V24" until the filament had been re-designed so as to give a saturation current four times the working current instead of, as expected, about twice.

Fortunately, the margins allowed in respect of noisiness and life both permitted the change without marked disadvantage.

With this modification these valves, called "R5," showed only one advantage in working over their collateral relatives, the "V24." They gave generally equal results in operation with a filament voltage just within, instead of just outside, the capabilities of a 4-volt accumulator.

The theory had thus been simplified to too great an extent and the final design of the R5 was really empirical, but the nature of the discrepancy between calculation and observation showed that either of these valves represented some approach to finality in valves of this type. All the small valves developed in the period covered by this paper, whether French, English, American, or German stopped at points not far from that here reached.

In standardizing these valves it was decided to adopt the bulb and cap developed by Captain Mullard for the Royal Air Force shortly before, at a time when it appeared that the demand for a rapid acceleration of output could not be met by the V24 owing to the manual skill required in its construction. The anode of the R5 was made short and wide in order to reduce the electrostatic capacity between anode and grid, a matter of great importance in high-power amplifiers. The actual capacity is 2·0 cm., and is less still when the filament is incandescent. It could, however, be further reduced by about 0·5 cm. if the anode and grid connections were not taken out side by side through the stem.

The R5 among high-vacuum receiving valves, and the R2A among the gas-filled types, mark the final stage of development as far as valves actually used in naval installations during the war are concerned.

There was another and very different type, however, the evolution of which was all but completed. This was a valve distinguished by having a grid consisting of a flat plate close to the filament and on the opposite side from the anode, also a plate. It was the outcome of a long series of trials undertaken by Professor O. W. Richardson and Mr. F. S. Robertson at King's College at the invitation of the Admiralty rather more than a year before. It gave characteristics identical in the usual working region with those of the "R" valve, thereby demonstrating that the cylindrical construction with grid interposed between filament and anode is more conventional than necessary.

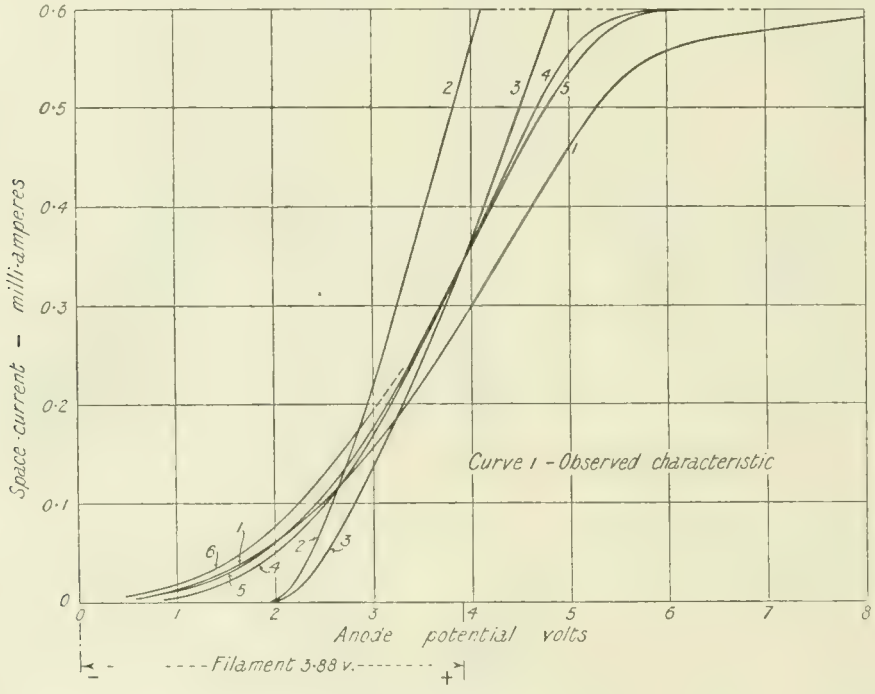


FIG. 22.

(9) VALVES WITH LOW OPERATING VOLTAGES, CALCULATION OF CHARACTERISTICS.

That it is possible to build up a theory which accounts with some approach to completeness for the several parts played by the various factors influencing the passage of current through a small valve may be illustrated by comparing an observed characteristic with characteristics calculated using successive stages of approximation.

Curve 1 in Fig. 22 shows the curve connecting space-current and anode voltage plotted from observations

on a small diode valve which was well exhausted and had a cylindrical anode of diameter 0·45 cm., i.e. the same as that of the grid of an " R " valve. The filament also was near to that of the " R " in diameter, 0·0057 cm., but its length was greater, 3·05 cm. instead of 2 cm. Each end of this filament would show an appreciable temperature gradient due to conduction to the supports for a length of 0·8 cm., leaving 1·45 cm. in the middle at a uniform temperature, which could be calculated from the diameter and the heating current.

In attempting to reproduce this observed curve by calculation we may start with the extreme assumption that the whole 3·05 cm. of the filament is active, and is all at the same potential, which we will take as that of the centre of the real filament, i.e. 1·94 volts, from the conventional zero at the negative end. Using Langmuir's formula we have

$$I = 2{\cdot}95 \cdot 10^{-5} (l_f d_a) (e - 1{\cdot}94)^{3/2}$$

and obtain curve 2. Simplification to this extent clearly takes away all value from the calculation here, although in most power valves it would have been quite legitimate.

As a next step, recognizing the extent of the end cooling given above, we may substitute for the full 3·05 cm. length of the wire the length of an equivalent filament, obtained by dividing the observed saturated space-current by the emission per unit length of a filament of the given diameter maintained throughout at the full central temperature. The revised length is 1·9 cm., and curve 3 shows the effect of the reduction. The approximation is closer, but not yet near enough for practical use, particularly as regards the top and bottom sections of the curve.

The largest stride comes with the next stage, where we allow for a uniform potential gradient along this equivalent filament, retaining the uniform electron emission.

Curve 4 is the result. Here Stoekle's * modification of Langmuir's formula would apply to the central portion, where the electrons constituting the space-current are drawn from all points of the filament, but it fails when any point is saturated, or is still inactive because its potential is positive to that of the anode. The method of obtaining the full curve, as shown, requires more detailed explanation.

In the method now to be described the temperature of the equivalent filament is supposed to rise to its full value at a negligibly small distance from the filament end. Such a filament is alike at all points along its length. If, therefore, we plot distance from the negative end against the supply of electrons available according to the temperature at each distance, we get a very simple diagram [Figs. 23 (*a*) and 23 (*b*)]. In this diagram the ordinate gives the total number of electrons which can be emitted by a small element divided by the dimensions of the element measured along the axis of the filament. As the voltage gradient along this ideal filament is the same at all points, the horizontal distances on the diagram can be taken as representing either centimetres from the negative end, or volts from the negative end. In the first case [Fig. 23 (*a*)], the ordinate is simply the total emission per unit length of the filament, i.e. in the usual notation, $i' d_f$; in the second, Fig. 23 (*b*), it is the emission per unit voltage displacement along the filament. Now the voltage per unit length is E'/d_f, where E', like i' above, is a specific function of the temperature. Hence in Fig. 23 (*b*), the ordinate is

$$\frac{i' d_f}{E'/d_f} \quad \text{i.e.} \quad \frac{i' d_f^2}{E'}$$

In both cases the value of a current is indicated by an area on the diagram.

This, then, is the distribution of the available supply of electrons in this simplified case. It is to be remarked, however, that the same form of diagram is equally applicable and very convenient in the case where allowance is made for a progressive fall of temperature as either end is approached. Stead's work on the design of short filaments can therefore be applied directly to the extension of the methods here developed.

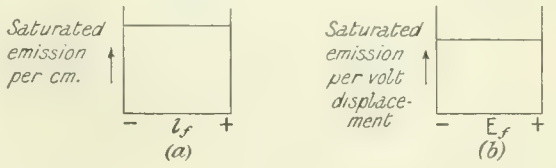


FIG. 23.

In a valve which is not entirely inactive through saturation, the whole of the available electrons do not, of course, take part in the space current. How many of them do so is a question of the field available for removing them from their starting-point on the filament.

As the voltage variation along the filament is not negligible, this field will be greater at the negative end than at the positive end, and as the voltage variation is assumed, for the present, to be ideally uniform, the field will decrease as in Figs. 24 (*a*) and 24 (*b*). If the applied potential is small, the field may be reversed at the positive end, Fig. 24 (*b*).

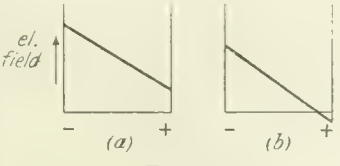


FIG. 24.

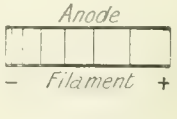


FIG. 25.

Knowing the field at each point of the filament, we can construct diagrams on the same lines as Figs. 23 (*a*) and 23 (*b*), but showing the distribution of the possible emission as limited by the field available at each point. Take an element of the filament distant λ cm. from the end and therefore at a potential E_λ, where

$$E_\lambda = E' \lambda / d_f = \lambda E_f / l_f$$

If the potential of the collecting electrode is e, the field at our element will be due to the potential difference $e - E_\lambda$, or very nearly so, provided the lines of force run straight across and do not bend appreciably towards either end (Fig. 25).

* E. R. STOEKLE : *Physical Review*, 1916, vol. 8, p. 535.

If the length of the element is $\delta\lambda$, the maximum electron current which this potential difference will remove will be

$$A\,(e - E_\lambda)^{3/2}\,\delta\lambda$$

i.e. the ordinate in Fig. 26 (*a*), where the horizontal distances denote actual distances from the filament end, will be

$$A\,(e - E_\lambda)^{3/2} \,.\, \delta\lambda/\delta\lambda, \quad \text{i.e.} \quad A\,(e - E_\lambda)^{3/2}$$

The constant A depends on the form of the electrodes, for a cylindrical valve it will be

$$\frac{2{\cdot}92 \times 10^{-5}}{\beta^2 d_a}$$ in amperes and cm.

The corresponding ordinate for Fig. 24 (*b*) with a horizontal scale of volts, is obtained by dividing by

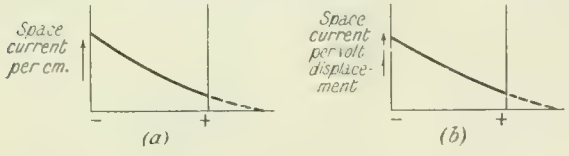


FIG. 26.

δE_λ, the voltage drop in the element $\delta\lambda$, i.e. by $E'\,\delta\lambda/\sqrt{d_f}$, and is therefore

$$A\,(e - E_\lambda)^{3/2}\,\frac{\sqrt{d_f}}{E'}$$

It must be noted that it is only because the voltage variation is uniform, i.e. because $d\,E_\lambda/d\lambda$ is constant all along the filament, that the two curves of Fig. 26 (*a*) and Fig. 26 (*b*) have the same form. Otherwise Fig. 26 (*a*) would be a more or less distorted copy of Fig. 26 (*b*).

From this point we will use the horizontal scale of voltage only, as in Fig. 26 (*b*).

If the field reverses before the positive end is reached, as in Fig. 24 (*b*), part of the filament will be idle (Fig. 27).

We are now in a position to show by superposing

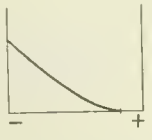


FIG. 27.

Figs. 23 (*b*) and 26 (*b*) the contribution of each element of the filament to the total space current.

Several cases arise.

In each case the proportion which the anode current actually flowing under the conditions shown bears to the total available supply of electrons is given by the relative sizes of the shaded area and the full rectangle.

Of these cases, those shown in Figs. 28 (*a*) and 28 (*c*) must clearly occur in all valves, Fig. 28 (*a*) at the very bottom of the characteristic curve, Fig. 28 (*c*) just before saturation is reached. Whether the intermediate condition is that of Fig. 28 (*b*) or Fig. 28 (*d*), will depend on the proportion of the strength of the field to the total supply of electrons. In a good receiving valve when the field can be strong, owing to the small grid diameter, and space-currents are small, we should expect Fig. 28 (*b*); in a power valve where the currents are large and the anode voltage has to be very considerably greater than the filament voltage before saturation is attained, Fig. 28 (*d*) will be the rule.

As the voltage applied to the collecting electrode is increased, the curve of limited emission [Fig. 26 (*b*)] will be displaced in the positive direction, and the shaded area correspondingly increased.

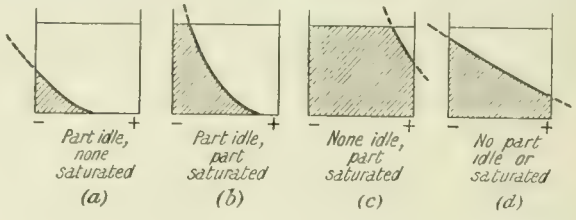


FIG. 28.

The increase in the shaded area for a given voltage displacement will be the measure of the slope of the characteristic.

Figs. 29 (*a*) and 29 (*b*) show by direct inspection the value of the slope under any conditions, because the height of the point of intersection of the two curves, or the difference of the two heights if there are two points of intersection, can be shown to be a measure of the slope. For, since the curve of limited emission is displaced without change of form, the increase of area [shaded in

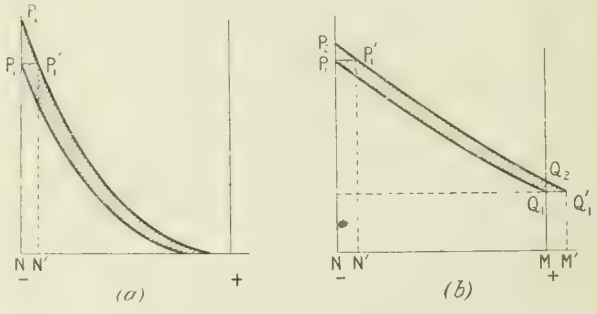


FIG. 29.

Fig. 29 (*a*)] may be supposed to be that included between the new ordinate of intersection, $P_2 N$, and the displaced old one, $P'_1 N'$. As the actual displacement employed is made less and less, this area becomes more and more indistinguishable from the product of either ordinate, new or old, and the displacement.* Hence we have :—

$$\text{Slope, } k, = d\,I/d\,e$$

$$= \frac{\text{Increase of area}}{\text{Voltage displacement}}$$

$$= \frac{\text{Area } P_2 N N' P'_1 \text{ between ordinates of intersection}}{\text{Voltage displacement } N N'}$$

$$= \text{Ordinate of intersection, } P_2 N$$

* It has been pointed out to the author by Mr. A. C. Bartlett that when P Q becomes sensibly horizontal the difference of the ordinates can no longer be taken to represent the slope; the effects of the filament voltage are then, however, all negligible.

If an intersection occurs on the right-hand vertical, the change of area will be less than expected by the area, $Q_2 M M' Q_1'$, Fig. 29 (*b*). In this case then the slope is given by the difference between the ordinates $P_2 N - Q_2 M$.

We can now write down expressions for $d I/d e$ in the various sections of the characteristic curve, beginning from the bottom :—

(*a*) Lower curved section :

$$d I/d e = \frac{A\sqrt{d_f}}{E'} \cdot e^{3/2} \quad \text{Fig. 28 } (a).$$

The 3/2 power of e appears because the length of the filament in action is proportional to e ; E′ is a specific function of the filament temperature as before.

(*b*) Central straight section :

$$d I/d e = \frac{\nu'}{E'} \cdot d_f^{3/2} \quad \text{Fig. 28 } (b).$$

(An approximately straight central section for a very hot filament has another explanation, see next paragraph.)

This expression for $d I/d e$ does not involve the dimensions of the collecting electrode, and holds for all valves, actual as well as ideal, provided that the filament temperature and the applied field are both low enough for the single intersection in the central constant temperature region to be obtainable [Fig. 28 (*b*)].

(*c*) Central section, not quite straight :

$$d I/d e = \frac{A}{E'} (\sqrt{d_f}) \left\{ e^{3/2} - (e - E_f)^{3/2} \right\}$$
$$= \frac{A}{E'} (\sqrt{d_f})\, e^{3/2} \left\{ 1 - (1 - E_f/e)^{3/2} \right\} \quad \text{Fig. 28 } (d).$$

As already stated, this expression applies to the case of a hot filament in a weak field.

If E_f is at all small compared with e, we have approximately,

$$d I/d e = \frac{A}{E'} (\sqrt{d_f})\, E_f \cdot \frac{3}{2} \cdot e^{1/2}$$

But $E_f = E' \cdot l_f/\sqrt{d_f}$, so $d I/d e = (3/2)\, A\, l_f e^{1/2}$, just as in the simple case of high-voltage valves where E_f is negligible. Curves have been calculated for intermediate cases where E_f and e are comparable in size.

(*d*) Upper corner :

$$d I/d e = \frac{\nu'}{E'} d_f^{3/2} - A (\sqrt{d_f}) (e - E_f)^{3/2} \quad [\text{Fig. } 28(c)]$$

and diminishes to zero when the intersection has passed beyond the upper right-hand corner of the diagram.

Returning to the case under consideration, curve 4 (Fig. 22) was obtained by means of Figs. 28 (*a*), (*c*), and (*d*). The two corners, upper and lower, show some approach to the observed form, and this approximation, imperfect as it still is, may perhaps be taken as the nearest likely to be of use in actual design, for at the next stage one can hardly avoid departing from algebraic formulæ and resorting to graphical methods.

As might be expected, one does come closer to the truth if one substitutes for the uniform emission and potential gradient assumed for curve 4 the distribution of temperature, and corresponding distributions of emission and potential gradient along the length of the filament obtained by Stead's method.

For our case this gives the emission diagram shown by the full line in Fig. 30 plotted with a horizontal scale of voltage. From this successive values of the space-current are obtained by placing the curve of self-limited emission (dotted lines) successively in the proper positions corresponding to the selected values of the voltage e and counting the squares under the dotted line and the parts of the full line which it cuts off. Curve 5 thus obtained is better than curve 4, though it is only at the bottom end that the improvement is worth the trouble. At the top end the departure is considerable, largely owing to the gradual approach to saturation shown by the observed curve. This effect is not covered by any existing thermionic theory, and has not been allowed for in our calculation. The error at the top of the curve is, however, somewhat

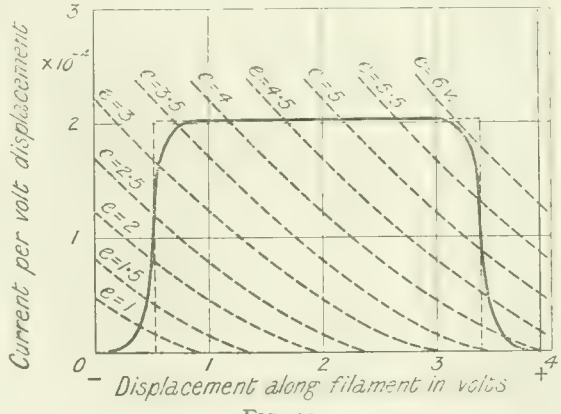


FIG. 30.

exaggerated in appearance owing to a false verisimilitude at the lower end, where some important effects have been left out of account.

In the first place, it is known that the extreme foot of the curve has an extension beyond the origin in the direction of the negative voltages. The scale of the diagrams is not suitable for showing this, but it has an exponential form and the current increases with change of voltage at the rate which would be expected if the distribution of velocities of projection of the electrons as they leave the filament is supposed to be the ruling factor. To make allowance for the velocity distribution in attempting to approximate further is therefore sound, though the rough method used in obtaining curve 6 is perhaps open to criticism. This was to suppose that the electrons leaving any particular portion of the filament with a high velocity behave in every respect as if they came from a point nearer the negative end by the fraction of a volt, by falling through which they would acquire this velocity. It is assumed that the proportion of the electrons from any point which have a given velocity is given by Maxwell's distribution law.

The second point is that curve 6 is displaced to the left of the observed curve by almost the same amount as the upper part of curve 5 into which it merges.

This means that we have now obtained a curve of nearly the right shape, except at the extreme top, but referred to a zero of potential which is displaced a few tenths of a volt with respect to the negative end of the filament. It seems reasonable to refer a zero displacement of this order of magnitude to the contact potential difference between the body of the hot tungsten filament and that of the cold nickel anode, especially since the zero displacement varies from valve to valve and the contact potential is well known to be very sensitive to changes in the surface condition of the metal electrodes.

In extending this theory to triode valves by substituting for the single anode voltage e the expression $e/m+e'$, combining the effects of the grid voltage e' with those of the anode voltage e, it must be remembered that in most small valves the value of m is by no means constant all along the filament, particularly when the ends of the filament are not sufficiently covered by the grid.

(10) Specification of a Standardized Valve.

It was always the practice to test each valve individually before issue. Uniformity as between one valve and another is a thing obviously desirable of attainment, seeing that the duties of an operator on service lie in other directions than the investigation of troublesome individual peculiarities in the valves issued to him. At first, when the action of valves was little understood, the test took the form of an actual trial in a receiver. This single comprehensive test was, no doubt, ideally satisfactory as long as the flexibility of the receiver and the simplicity of requirements make it a test which all of the valves pass; but it is often the reverse of illuminating when rejections begin to appear. Experience showed more than once that unless the physical cause of failure was explored and eradicated on its first appearance, the proportion of defective valves was liable to grow at an alarming rate. Testing by the pragmatic method also becomes impracticable as valves come to be used in different instruments.

The alternative of taking steady current conditions and making tests which amount to observing a few suitable points in the working region of the characteristics under standard conditions of filament adjustment, was gradually substituted, tests in a receiver being confined to special or doubtful cases, and ultimately eliminated.

A set of essential test conditions for a valve for general use in receiving instruments, amplifiers, heterodynes, or detectors was ultimately arrived at by summing up the experience of the members of a small committee which jointly represented the Admiralty, War Office, and Royal Air Force in furthering the rapid expansion of valve production in this country which took place during 1918. The committee was very fortunate in its composition, and the respective shares of the members in the details of the outline specifications which summed up the technical aspects of their work would be difficult to estimate. What follows is an account of methods which the author found useful in exhibiting the results of tests and trials during the transition from the easy specifications of the early days of simple heterodynes to the stricter requirements of amplifiers and other later types of instrument.

For the purpose of scrutinizing test results, observations on valves were considered under two heads. First, there were the current and voltage adjustments required to produce a specified saturation current of electrons from the filament, and secondly there were observations indicating the form of the characteristics in the working region when the filament had been so adjusted.

Taking the case of the filaments, the current and voltage adjustments for 100 valves may be shown together by representing each valve by a dot on a diagram such as Fig. 31 where the horizontal axis represents "volts" and the vertical "amperes." The figure gives an actual case for 100 filaments of fairly pure tungsten. The diagonal line is added to show, for an average valve in the centre of the group, the normal course of current variation as the voltage adjustment is changed. Any valve appearing below

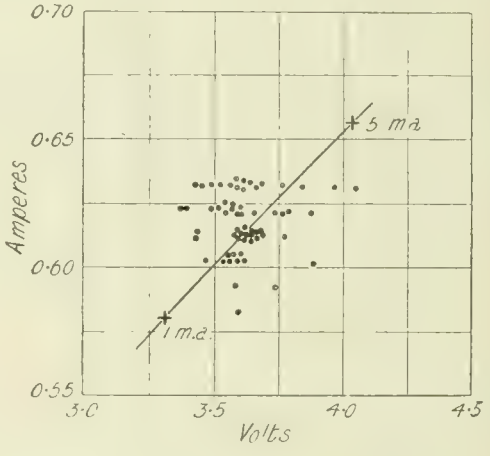


Fig. 31.—Filament adjustments for 2 m.a. saturated emission.

this line requires abnormally high voltage for a given current, and is therefore probably either longer or else thinner than the average, the latter defect being usually traced to damage during bombardment. Similarly points above the line represent filaments either thicker, or, more probably, shorter than the average. As each valve is adjusted to a given emission, points occurring in positions close to the line represent differences in electron-emitting properties. The extent of the differences in the batch shown is indicated by the crosses on the line giving the adjustments of the average filament for 1 and for 5 milliamperes as well as for the usual 2 milliamperes.

The best emitters are seen to give 2 milliamperes where the average would give $1\frac{1}{2}$, and the worst 2 instead of 4.

The diagram thus illustrates how the variations of the thermionic property which, not so very long ago, was regarded as very fickle, have been brought within bounds. With specially selected specimens of metal target, diagrams covering one-third of the range shown

have been obtained. A tendency for the group to extend upwards in the direction of poor emission is found to be associated with imperfect exhaust (cf. Langmuir's work on the effects of residual gases, thus statistically confirmed),* and on the other hand extensions in the opposite direction indicate impurity of the tungsten, and are especially well shown where thoria is present, and also give warning of probable noisiness in amplifiers.

The earlier observations of standard points on the characteristics made very conspicuous the fact that the characteristic "constants" of small high-vacuum valves differ among themselves very widely. This is so even when the valves are all well exhausted and to outward inspection well made. The factors most

FIG. 32.

observed, the records covering many thousands of valves, were

Anode-current/grid-voltage slope, k_1.
Anode-current/anode-voltage slope, k_2.
Grid closeness factor $m = k_1/k_2$.

In any batch of 100 valves or so the lowest value of any of the above quantities is commonly as low as one-half of the highest value observed in the same batch.

The characteristics are thus actually almost as variable as the life of the valves.

Fig. 30, in which each dot gives simultaneous values of k_1 and k_2 for a particular valve, shows the range of variation occurring in an ordinary batch of valves. The diagrams for all types of high-vacuum valves of which sufficient numbers have been available—R4, R4A, R4B, R5, R, and V24—show the same degree of variation, and gas-filled valves still show the same effect even when, as in R2A, which is a true high-vacuum valve before the gas is admitted, there is no question of variation in the quantity or nature of the gas.

One of the first uses to which these diagrams were put was in making minor modifications in the construction of valves by different makers so as to bring the average in each case midway between the specified limits.

In determining the limits of the permissible range of variation in respect of a particular characteristic quantity for a particular receiver in which the valves are to be used, subsidiary diagrams of the same type were used.

In Fig. 33, for example, each pair of dots shows horizontally the anode-current/anode-voltage slope k_2 for a pair of valves used together in a two-valve audio-frequency amplifier. The two valves of each pair were selected as having as nearly as possible the same k_2, but in respect of all the other characteristic quantities all the valves taken were allowed to vary in an arbitrary manner. The vertical scale of Fig. 33 gives an inverse estimate of the sensitivity of the combination, the quantity represented being the coupling required for obtaining a signal of standard strength, so the smaller the coupling the greater is the sensitivity.

The way in which the dots arrange themselves, in

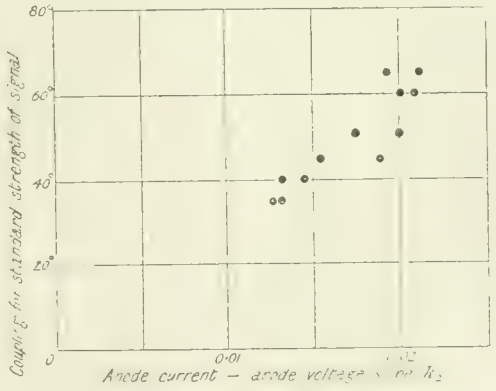


FIG. 33.—Effect in amplifier of changes in a characteristic.

an elongated diagonal group, indicates that the anode-current/anode-voltage slope has a very marked influence on the sensitivity independently of all other factors, but that the two combinations, themselves somewhat unlikely, of a pair of good, and a pair of bad valves, differ in respect of the necessary coupling in a ratio of no more than two to one, which represents with the apparatus used about one signal "strength." Considering that the range of variation of k_2 covered by the group is nearly two to one, this observed effect is somewhat surprisingly small. This is, however, just as well, for reference to the full test diagram (Fig. 32) shows that it would have been possible to find worse valves in either direction of variation. The fixing of specified limits for k_2 at 0·0225 and 0·012 milliampere per volt, finally decided upon from trials in this and other pieces of apparatus, involved a considerable proportion of rejections, but practice in manufacture ultimately gave some improvement. In all cases

* LANGMUIR: *Physical Review*, 1913, vol. 2, p. 450.

where the valves were intended for multiple-valve receivers it was decided that the probabilities were so much against an operator being forced to use a combination of valves all differing to a marked extent in the same direction from the average, that tolerances giving extensions in respect of the limits for a limited proportion of the valves were permitted in some cases.

In some of these trials it was found that the quantity under observation had no direct influence on the effectiveness of the receiver, the form of the group on the diagram being either circular, or a circle distorted by purely vertical or horizontal elongation. This was the case, it is of interest to note, with the anode-current/grid-voltage slope in the audio-frequency amplifier.

The narrowest limit required for each characteristic quantity by the most exacting receiver can be shown by a line on Fig. 32, and the size of the group relatively to the frame of lines so formed indicates the strictness of the specification or, conversely, the quality of the manufacture. A general displacement of the group shows by its direction which factors tend to be at fault, and the effects, often unexpected, of steps taken to remedy such faults can readily be followed. It is apparently established that variations of m are caused more by differences in the extent of exposure of the filament ends than by irregularities in the convolutions of the grid itself, and that simultaneous low values of both anode-current slopes, k_1 and k_2, are due to a specially large change of contact potential in the direction of retarding the electron flow.

The electrical tests decided to be necessary for receiving valves were as follows:—

Filament.—An upper limit, imposed by the supply arrangements, for the current and voltage for a specified saturated electron current, and a lower limit of voltage if great uniformity is required, or valves are used with a common filament control.

Characteristics.—Anode current observed at two stated grid voltages and two or three anode voltages, the differences of readings indicating the values of the characteristic slopes and of their ratio m. Lower limits are specified for both slopes, and for m, but an upper limit for the anode voltage slope only.

The value of the reverse grid current, if any, at a stated negative grid potential is taken as indicating the degree of exhaustion of the valve, and the direct grid current at the working grid potential as indicating the damping effect of the valve on the input circuit.

Life.—Sufficient information for rigid life-test clauses was not available at the time considered.

For power valves the filament specification followed the same lines. A power-dissipation test of a few minutes' duration for the anode was included, and this was to be carried out under such conditions that the space current actually flowing was less than the saturation current which the filament had been previously adjusted to give, and was therefore controlled by the voltages of the other electrodes and by the space charge, that is, by the state of exhaustion.

A dissipation test so carried out gives a clear indication of the stability of the valve as regards the vacuum.

The testing of each individual valve on these lines was quickly learnt by previously untrained testers, and was carried out with very satisfactory accuracy, with the result that complaints of electrical misbehaviour of valves became very rare.

In conclusion, the author desires to express his thanks to the Captain of H.M. Signal School for assistance in the preparation of the paper. It is impossible to indicate how much the author's own share in the work described has benefited throughout so long a period by the co-operation of Professor Fortescue, of Mr. Stead, and of the various members of the wireless telegraph departments of H.M.S. "Vernon" and of H.M. Signal School, particularly by that of Mr. T. E. Goldup, late Lieutenant R.M., and Mr. C. O. Moss, late Warrant Telegraphist R.N.R., in their unfailing help in the work of standardization described in the later sections.

He wishes also to make some acknowledgment, however inadequate, of the ready kindness on all occasions of those with whom he has been privileged to confer, whether in the discussion of physical principles, or of the action of circuits, or of practical considerations in manufacture.

APPENDIX.

(*Received* 4 *October*, 1920.)

When the paper was read before the Institution use was made of a three-dimensional model to illustrate certain internal actions of the valve. The object was to represent to the eye the motions of electrons in an electric field by the analogy of those of a ball rolling on an undulating surface, the differences of level on which reproduce potential differences between the corresponding points in a longitudinal section of a cylindrical valve. The actions resulting in the control of the space-current through the valve are essentially dynamical, and it is necessary to adopt some such representation as this in which allowance is readily made for the momentum of the electron which prevents it following a curved line of force.

The ordinary line-of-force representation of the field shows directly only those lines along which an electron in free space will certainly not move, for the electron will only follow the line of force in the exceptional case when this is perfectly straight. A diagram of equipotential lines is more useful, but even so it is necessary to visualize the surface of which it is a contour map.

By imagining such a surface one can readily trace out the effects of a change in the potential or in the shape of an electrode. The composite potential function $e/m + e'$ in the triode acquires a more concrete significance as the level of the sinuous equipotential which winds in and out of the row of grid wires and indicates what is for the other electrodes the average or effective

potential in the plane of the grid. The partition of the electrons between anode and grid is also sufficiently explained without recourse to the mathematical analysis of central forces, and the effects of the velocities of projection of the electrons and of the space charge can be allowed for, but the effort of viewing the surface as it were from the other side, or alternately of reversing the supposed direction of gravity, in order to represent the field from the standpoint of a positive ion is unfortunately usually too much for the imagination.

Discussion at a Wireless Sectional Meeting of The Institution, 23 June, 1920.

Professor C. L. Fortescue: Problems which, in the early days, seemed formidable now appear, as we look back upon them, quite simple, but at the time we were struggling with them they were very real, and such success as we achieved was due in no small measure to the persistent zeal with which the author attacked them. In the course of investigating these problems it was interesting to note the extent to which we reached at times the limits of knowledge. A lot of the work done on the valve was really almost pure research, and the valve actually produced was a good example of pure research running in parallel with its immediate application. Almost any paragraph of the paper would provide a text for a long discussion, and I propose therefore to deal with only three points. The first is the question of the contour diagrams on page 684. This method of delineating the characteristics of the valve was devised by the author of the paper and has proved to be very useful, and I know of no other method of bringing out so compactly and clearly the whole of the necessary properties of the valve, either from the point of view of the physics of the valve itself or from that of the circuits associated with it. They have many other advantages, particularly as regards the transmitting valve. In the great majority of transmitting-valve circuits the trace of the variation of the grid and anode voltages becomes merely a straight line drawn across these contours, and they tell immediately what the nature of the currents will be, what conditions will lead to the presence of harmonics in the make-up current, and so on. They also have the advantage that they can be actually obtained in practice. If one takes Fig. 16 (*a*), for example, a very few points on all those straight lines are all that are necessary. Next I will consider the target diagrams. I think those who are inclined to regard the valve as having very definite constants should consider Fig. 32 carefully. There is no doubt whatever that the range of variation actually found in practice explains many of the difficulties which have been met in high-power amplifiers. There are amplifiers where a small percentage change at one of the steps will cause either oscillations or a falling-off of the amplification. The standard of uniformity necessary is higher than shown in these diagrams, and steps will have to be taken, perhaps as one of the immediate lines of research, to secure a higher degree of uniformity. The last point I propose to mention is with reference to the question of symbols. Every worker on valves seems to have adopted a notation of his own. It is time that this Wireless Section settled whether they are going to keep to the k_1, k_2, etc., as adopted in this paper, or to use Dr. Eccles's notation, or to adopt the American notation. I suggest that the Wireless Sectional Committee should take the matter in hand and at any rate decide it provisionally. It is not necessary to reach a final decision, but we can come to some temporary agreement until something better is put forward. Leaving the actual subject matter of the paper, I should also like to refer to the Valve Committee. That was formed in 1918 under rather adverse conditions at a time when the supply of valves for the various Services was far from sufficient. It took up the matter of the supply of valves, and had a lot of difficulties to overcome, as there was a certain amount of opposition. But after its formation the supply of valves never actually failed, although perhaps there was not always a big reserve. The Committee did not do everything that was expected of it, but it certainly did what was wanted. The wireless branches of the different Services are indebted to that Valve Committee to no small degree.

Mr. C. C. Paterson: This paper shows how very good is the historical method of presenting any subject. The author has described all the stages of pioneer work in their chronological order up to the time when valves of all types were turned out on a production scale, but he has said very little about his own work in connection with this matter, although the results achieved were largely due to his tact and originality. As one who saw a good deal of this work from the manufacturing point of view, but who was not in any way responsible for it, I would say that this whole subject of the production of the valve from its early stages is of quite as much interest from the point of view of industrial research as it is from that of radio research. One first of all appreciates that it was only achieved by both the technical people who were responsible for the development of the valve, and the manufacturers who were responsible for its production, each appreciating the difficulties which the other found. There were many difficulties to surmount on both sides. The technical staff of the Services were being pressed hard all the time to produce something which would work. The manufacturers were up against enormous difficulties in production under war conditions. They were having to use substitutes in a large portion of their manufactures, and men on whom they depended were being taken away from them for war service. Yet, in spite of all this, this country undoubtedly led the way in development and progress in connection with thermionic valves. I think it is very much to the credit of this country, and also of those who had any share in the work, that this result was achieved. Another moral to be drawn from this is that, as Professor Fortescue has said, the development of the valve was not the result of research handed over to the manufacturer to get into production, but the fundamental research had to proceed in parallel with the actual effort to produce

[illegible] The manufacturer had to adopt the hit-or-miss method to try to get something going, but he was supported throughout by the more fundamental research which followed but seldom preceded the production of the actual result. That is the way in which, in my experience, industrial research very frequently proceeds.

Professor G. W. O. Howe: This paper emphasizes a remark that I made at a previous meeting of the Wireless Section. Many of us thought in the early days after the war how little had been done in this country compared with other countries, but the papers which have been read before this Wireless Section during the last year, and this paper to-night, show that we were in no way behind, and that an enormous amount of valuable research work was being done under very trying conditions. I should like to express my appreciation of the ingenious model which the author has prepared. There is one point about it which I think might be made a little clearer in explanation of the action of the space charge. Many people probably experience the same difficulty as I had when I first studied the subject. If the electrons are emitted from the filament into a field which tends to repel them back to the filament, one would expect that either one would get no current due to the electrons all being driven back to the filament, or else one would immediately get the saturation current. I do not think it is usually sufficiently appreciated that the value given for the velocity of the electron emitted from an incandescent filament is only an average, and that the electrons are emitted at very different velocities. The distribution of the velocities follows a well-known law, and although the electron has an average velocity of the value quoted by the author from $\frac{1}{4}$ volt to $\frac{1}{2}$ volt, some of the electrons are ejected from the filament with a much lower velocity, and some with a velocity of 4 or 5 volts. What actually happens is this: if the height of that little hill in front of the filament on the model represent $\frac{1}{4}$ volt, it is only those electrons which are emitted with a greater velocity than $\frac{1}{4}$ volt that succeed in getting over, and all those below $\frac{1}{4}$ volt fall back again. If the voltage of the grid is raised a little the height of that hill will be altered, in fact will be lowered, and now a greater proportion of the electrons emitted will be enabled to get over the hill. By altering the grid voltage we vary the height of the hillock and thus alter the proportion of the constant number of electrons emitted that are capable of getting over and thus avoiding being returned to the filament.

Mr. J. St. Vincent Pletts: I was very interested in the model. The chances seem to be very much against the marble getting into the grid, but I should have thought that many more would have gone in than appears to be the case. I doubt if in that model even one in a thousand would get in.

Mr. J. Scott-Taggart: The design of valves may be classed into mechanical and electrical design, the former being almost as important as the latter. Figs. 9 and 10 show two very ingenious methods of constructing valves of high power. The problem in the case of these valves is chiefly the method of supporting the electrodes within a tube. There are two re-entrant tubes, one at each end of the bulb, and to these tubes are attached the supporting wires which hold the electrodes. Two methods are shown in this paper. One consists of metal bands which grip a stem, and in the other the anode is supported by means of springs which expand inside the tube and so hold the electrodes. There are one or two points to consider when choosing a method of supporting electrodes within the valve. The different electrodes should be so arranged that the insulation between them is exceedingly high, with a view to preventing leakage when high voltages are used. Another point is the rigidity of the electrodes. This is of special importance with valves which have to be transhipped. The rough treatment in the handling of the goods naturally requires the utmost rigidity of the internal structure of the valves. Again, in connection with the design of the valve from the structural point of view, there is the necessity of avoiding any glass-work which is liable to crack. Consequently, the ordinary arrangement whereby the supporting wires are fused into the glass stem cannot be employed on the higher-power valves, but some method must be devised

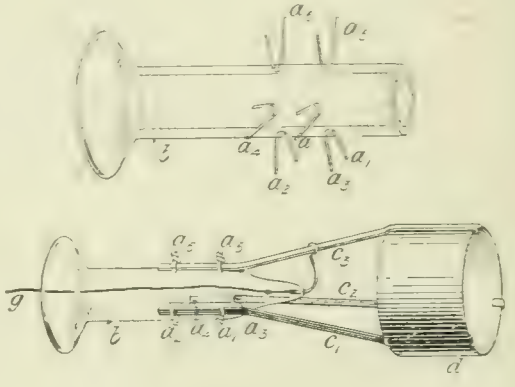


FIG. A.

whereby the structure is extremely strong without employing any glass-work. Again, there is the ease and cheapness of manufacture. Still another point of importance is that the metal parts inside the valve should, during the bombardment of the electrodes, be also bombarded, so that no portions of metal which do not have the occluded gases removed should be inside the tube. When I had to design the internal structure of the valves made by the Ediswan Company, several methods occurred to me, but I found that practically all of them had already been patented by the Osram Company. I eventually thought of the arrangement shown in Fig. A herewith. The upper figure shows a glass funnel which is sealed into one end of the bulb, and it is to this funnel that the electrodes are to be attached. The method that is being used is to take a number of small U-shaped wires, as shown, made of nickel-iron alloy having the same coefficient of expansion as glass, and dip them just below the surface of the glass. Being arranged in the manner shown, the supporting wires, which should preferably be of channel cross-section, are then slipped in between the wires. The two ends of each wire are

then twisted together and thus firmly tie the supporting wire to the glass. The completed stem showing an anode mounted is seen in the bottom figure. This construction has been found extremely strong, much stronger than would appear from the diagram, and, moreover, the chances of cracking are extremely remote. Out of hundreds of these valves that have been manufactured there have been no cases of cracking of the glass, and no particular precautions for annealing are necessary. Another advantage of this arrangement is that the anode is very securely attached. There is no fear of its slipping round, and no complicated arrangements are necessary. Another point is that there are no metal bands or large surfaces of metal which do not actually come under the influence of the electron bombardment. There is only a short distance which is not actually exposed to the influence of the electron bombardment, and consequently a higher degree of exhaustion is possible, or, alternatively, the same precautions are not necessary in the manufacture of a valve designed on this principle. The lantern slide illustrates an arrangement whereby the filament of a valve may be supported. This is a very difficult problem in a valve, and the usual arrangement has been to support the top end of the filament from the other end of the tube. This necessitates a rather more difficult method of manufacture, and at the same time there is a liability of leakage from the top end round to the electrode which is attached to the stem at that end. In this arrangement I have used a supporting wire tied to the glass stem which holds the filament wires, thus producing a very strong and efficient method of supporting filaments for rectifiers and high-power three-electrode valves. It is to be noted that this supporting wire is usually of nickel, while at the very top I use a small piece of molybdenum wire to prevent damage to the filament when the latter is incandescent. Another slide shows a small-power rectifier capable of dissipating about 250 watts. It will be seen that the anode and filament are mounted at the same end of the bulb. The anode is attached to the stem before the latter is sealed into the bulb. Consequently, the manufacture is very much cheaper and it is quite suitable up to comparatively high voltages. The danger is that sparking may take place through the glass between the anode supports and the filament wires. To prevent that, the filament wires are covered with very thick glass tubing, and this arrangement has been found very much cheaper to construct than the usual type in which the anode is mounted at the other end of the bulb. Mention has been made of the difficulty of manufacturing the V24 valve designed by Captain Round. This difficulty, I think, has been very largely exaggerated. This type of valve is, from the point of view of the manufacturer, probably one of the best that has been produced, and the breakage is exceedingly small. The valve is extremely light, and if dropped suffers very little. The connections are made at the sides of the tube, and so there is an infinite resistance between the anode and filament and between the grid and filament. This is a most important point in valve construction, and a considerable number of valves of the four-pin type, and also of the Air Force " C " and the Navy " R5 " types, are rejected at the works on account of leakage between the different electrodes, not inside the bulbs but between the leads outside. The caps used are attached by means of cement, which is naturally moisture-absorbing, and after a time the insulation is liable to deteriorate. Another advantage is that the capacity of the electrodes is probably less than in any other type of valve. The leads are taken direct to the outside and do not run parallel, as is the case in other types. A further slide shows a valve (known as the RV30) somewhat on the lines of the V24, which possesses all the advantages due to the absence of leakage and to minimum capacity of the electrodes. There are one or two points of interest. First, the anode support is fixed to a glass cup by means of the tie-on construction which I have explained. Another point is the nature of the glass cup, which provides a very long leakage path between the anode to the filament and between the grid to the filament. The leakage path between the grid and anode is also long. Turning to the original paper, there are one or two features in some of the designs which could be improved. The supporting of the filament of R5 valves is inadequate. The thin spring wire gets heated throughout its whole length and loses its elasticity. During the manufacture of these valves, this lack of efficient filament springing causes a considerable amount of breakage when on the pumps. If the spring is too tight the filament on shrinking is liable to snap ; if too loose, the filament is liable to touch the grid ; in each case, valves are spoilt. The tension on the R5 filament appears to be too critical. As the end of the spring wire is pulled down the tension increases. If, however, the flat spring wire is given a double loop and thus made about twice as long, the tension on the filament is less dependent on the adjustment of the spring during manufacture. A trial of 200 valves with such filament springs showed a saving of 15 per cent in filament breakage. It was also found on other valves that an additional spring wire at the bottom still further reduced the breakage during manufacture and also in transit. With regard to the grid of the R5 valve, it appears to be of a smaller diameter than necessary. Decreasing the grid diameter may even lower the amplification factor, and certainly does increase the cost of manufacture, as does also the asymmetrical placing of the grid and anode with respect to the filament. The backlash test for vacuum is not infallible. The current to the grid is the algebraic sum of the electrons and positive ions striking the grid. A " hard " valve in which the electron current to the grid was below normal might thus be considered "soft." It is to be regretted that in this paper no mention has been made of rectifying three-electrode valves. From the title of the paper one would have expected some description of the design of valves for purposes other than amplification.

Dr. W. H. Eccles: One of the most noteworthy of the numerous details of information in the paper is the formula for the voltage factor. I have myself worked out a formula for another type of grid and this formula is identical with the one in the paper, when Maxwell's analysis of the plane problem is extended

to determine an undetermined constant in my formula. It is to be hoped that the method of obtaining the formula in the paper will be divulged some day. In answer to a question by one of the speakers, I might mention that the Wireless Sectional Committee have several times had under consideration the possibility of doing something towards standardizing notation and symbols. It is, however, a difficult problem. The fact is that wireless telegraphy and telephony are developing so rapidly that any nomenclature suggested might soon become obsolete. We have seen that happen in the history of other electrical ap aratus. The present chaos is a kind of preliminary stage, but in another few years I believe we shall have a better chance of getting agreement between the people who have to use these symbols. I think that is the view of the Wireless Committee. For my own part I think it would be lost labour to go far at present. As an instance of the difficulty of persuading people to use standard symbols, the authors of English textbooks and papers use the letter " m " to stand for metre, or milli, or micro-, or mega-, indiscriminately. We often see microfarads written " mfds," contrary to the recommendations of the International Electrotechnical Commission. The same author in the next line will write " mhy " for millihenry, " m " in one line standing for " micro-," and in the next for " milli." I suggest that " wireless " authors might begin disciplining themselves by using the International Electrotechnical Commission's recommendations. Meanwhile the Committee will keep the matter before them and decide when the time is ripe for action.

Mr. H. M. Dowsett (*communicated*) : Having regard to the series of processes to which the gas atoms are subjected in a " soft " valve, it is a noteworthy achievement to have developed the theory of this valve to such a point that it is possible to predetermine the characteristics of a given design. To enumerate these processes : (1) There is first of all the break-up of the neutral molecule and the surrender by it of as many electrons as correspond to the atomic number of the element concerned. (2) The bombardment of the anode by the negative ions and the passage towards the filament of the positive ions. (3) The entry of the positive ions into the space charge and their reaction on it. (4) The bombardment of the filament by these atoms and their reflection from it as negative ions towards the anode or the walls of the valve. There are two of these states which call for some further remark. It is an accepted fact that the positive ion is able to neutralize much of the effect of the space charge. How it does so is a moot point. As the atom is travelling towards the filament it is probable that it fails to hold any electrons which are proceeding towards the anode, but they stream through it until it strikes the filament. At the same time, as the axis of the atomic magnetic field corresponds to its axis of translation, the space-charge electrons which are moving erratically and not towards the anode will be caused to whirl in spirals round the atom, forming a funnel up the centre of which the newly expelled electrons from the filament will find an unimpeded path. After the atom has struck the filament and its direction has been reversed, it will take up its full complement of electrons or an excess depending on the space potential, as it will now be proceeding in the same direction as the electrons, and in this way it will tend to reduce the space charge. All these electrostatic and magnetic effects are fortunately proportional to the atomic weight or the atomic number, and this must be held to explain why predetermination is not a more difficult matter.

Captain H. J. Round (*communicated*) : The author has brought together in this paper a very large amount of information on the details of design and construction of valves which has been in the last few years both secret and scattered. Although a few of us have had access to some of the work recorded in the paper a great deal of it is quite new to me, particularly the splendid series of soft-valve characteristics. The paper, in fact, records such a mass of work that a satisfactory discussion of it would take up much more space than the paper itself. I find that I have had to concentrate on one or two parts of the paper and leave the rest for reference when the subjects referred to become of interest. I think it is rather a pity that any space at all is given to the American ultraudion circuit. To synthesize a good circuit is far more useful than to analyse and patch up such an arrangement. In connection with this ultraudion circuit, E. A. Armstrong gave a similar analysis of it in a communication to the *Radio Institute Journal* about two years ago. Mr. Gossling's paper teems with characteristics of various valves, but the relation of these to circuits, and an indication why such and such characteristics are valuable, would add to the completeness of the paper. Perhaps I am asking too much, as I am aware that the paper was written with the idea that it is generally known what characteristics are wanted. How these characteristics were obtained by theory and experiment and reproduced on a manufacturing scale is the author's special province. I think we are waiting for our Chairman or another to collect together into one comprehensive book or paper all the specialist papers on valves and valve circuits. The collected work on soft valves is a very valuable contribution, and most of it is quite new to me. I should like to know to what extent the static characteristics are relevant in high-frequency work. The paper still leaves me in doubt as to whether magnification by ionization is possible, and up to what order of frequency, and whether it occurs to any practical extent in soft valves. One can feel fairly sure that with frequencies such as 50,000 ∼ per second hard valves obey the static characteristic laws, but is this true with soft valves ? I am strongly of the opinion that practically all the advantages of a soft valve are obtained, due to the neutralization of the space charge and the consequent lowering of the resistance of the valves. Static characteristics would, by showing the sum of the negative and positive currents, give a false idea of the operating characteristic. Wherein lies the value of a soft valve ? This question of course introduces the additional question : For what use do we require the valve—as a rectifier or a magnifier ? I can answer the last part of the question by making the practical statement that a soft valve has nearly all the properties of a bank of hard valves in parallel. In other words, the soft valve has for its " m " value a very low resistance

compared with the hard valve. The "m" value of a valve can be defined as the maximum voltage amplification possible when using a resistance-drop amplifier, when the resistance and the plate voltage are both infinite. If we replace the resistance by a resonant circuit and consider the voltage amplification when using frequencies exactly in tune with this circuit, we can say that the "m" value is now the voltage amplification when the damping of the circuit is zero. The plate potential now of course need not be infinite. Suppose, however, that damping is now applied to the circuit; the actual "m" value is then less than the maximum by a factor depending upon this damping and upon the resistance of the valve. In general, the lower the resistance of the valve, if its maximum "m" value is kept constant, the nearer the practical "m" approaches the maximum "m." The value of damping in the plate resonant circuit is well known in "quasi-aperiodic" amplifiers. Again, in "quasi-aperiodic" low-frequency magnifiers where a ratio transformer is used to the next valve grid, the lower the resistance of the valve the higher is the ratio of step-up transformation that can be used—depending on the effective losses in these transformers. All these advantages are of course dependent upon the fact that the internal capacities of the valves do not exhibit such low impedances that applied voltages on grids, for instance, are appreciably lowered. The real point in the soft valve is this: that at reasonable plate voltages high practical magnifying power can be obtained. The actual working capacities of soft valves do not seem to have been determined, but there is probably a considerable increase over the static capacities of the tubes. General consensus of opinion seems to indicate that with hard valves the working capacity is not appreciably different from the static capacity. Recent work has enabled us to obtain with the four-electrode hard valve all the advantages of the soft valve with the dimensions, filament and plate voltages, and filament current of the V24 valve. One set of hard valves which we are now manufacturing and shortly intend to place on the market has the same internal resistances as a V24, but with an "m" value of 30 instead of 6 as in the V24. The benefit of this on a cascade resistance-drop amplifier can be at once seen. The capacities of these valves are still small compared with those of clips, leads, and windings. I should like to note that in the use of Sir J. J. Thomson's formula for the "m" value it is usually sufficient to use a value $\pi d n$, where d is the grid diameter, and n = no. of turns per cm. length; or, in the case of a square mesh, $2 \pi d n$; providing always that the diameter of the wire is small compared with the spaces. This value is obviously the amount of wire per cm. length of grid. Further correction is best done experimentally by testing a number of valves.

Mr. B. S. Gossling (*in reply, communicated*): More than one contributor to the discussion has remarked upon the general characteristics of research in such subjects as that with which the paper deals. It is a fact that the greater part of the work there recorded is of a nature essentially analytical. Here is an instrument which works—sometimes at least—in such and such a manner. What is really going on? The attempt to answer such a question is a necessary part of the work of institutions, such as H.M.S. "Vernon," to which inventions are referred, and, again, as Mr. Paterson says, such work is more often subsequent than precedent to actual manufacture. In both cases it is the hand which has been dealt that has to be played, and the unexpected usually happens. What methods will be necessary, and into what fields of knowledge it will be necessary to make excursion, it is difficult to predict. Professor Fortescue will agree that a conscientious analysis of the commonest of phenomena is liable somewhere to touch the confines of knowledge. Encyclopædic minds being too rare to count upon, and usually otherwise engaged, the most promising course is for a number of specialists who cover between them all likely fields to agree to pick one anothers' brains. Such collaboration was one of the commonplaces of the war. The cultivation of the surviving relics of this spirit is a present-day problem. The analytical nature of the work recorded is well shown by the fact that, although many fundamental physical principles underlying the behaviour of valves there become recognized, no new principle not operative in one or other of the valves of 1914 has been enlisted during the period covered. However, one is entitled to hope that the analytical work of the past, besides leading up to rational standardization and deliberate design, may have resulted also in an enlargement of the opportunity for work of a different order.

Synthetic research in applied science (if I may borrow Captain Round's wording) requires a wide knowledge of the art in question such as comes slowly and to few, although direct and preferably untrammelled contact, alike with operators, manufacturers, and inventors, is an invaluable aid and a never-failing stimulus to the imagination. The synthetic attitude of mind is not quite that of the inventor, as the analytical is not quite that of the consultant, but the distinction is at least of the same order. The purely scientific equipment required may be the same in both cases, just as the possession of a common language has its uses, but the differences are differences of method and object, and more may be heard of them in the future, when a precise definition of the nature of professional research work is attempted.

The symbols employed in the paper are the same as those used by Professor Fortescue in his own published work. I do not doubt that we are equally aware of their drawbacks, but I gather that he, like myself, has felt, in the absence of an authoritative pronouncement, transcription would be wasted labour. Adoption of recognized conventions may call for some additional alternatives to standard symbols. For instance, the chief expression in the theory of the distribution of electron velocities involves the "exponential e," the electronic charge, and a symbol representing volts. For work in this field each of these quantities must have a different symbol. Which is to be called "e"?

The lack of uniformity amongst different specimens of small valves of the same design can be ascribed in large measure to variations in contact potential, which result in the field experienced by the electron near an

electrode being different from that which would be expected from the indications of a voltmeter connected to that electrode. These effects usually show themselves as a bodily movement of the current/voltage characteristics without change of form, and in diagrams of the type of Fig. 32 by motion of the indicating dots towards or away from the origin. The use of a grid-leak largely compensates such variations. Research on so important a point is certainly needed, more particularly as the subject of contact potential is still in the same nebulous state as were thermionics at the time when valves were first invented.

The point about the space-charge raised by Professor Howe is of vital importance. The reason why currents are observed which are less than the saturation current is to be sought in the fact that the electrons possess inertia and therefore require time for their transit, however great the attraction to which they are subjected. At any instant, therefore, between the present position and the ultimate goal of an electron which has but just left the filament there will be found a number of other electrons which have preceded it but have not yet completed their path. The first electron is subject to repulsive forces due to these preceding electrons in addition to the attraction of the anode, and the greater the space-current the greater will be the number of electrons in transit and the less the resultant attraction on those near the filament. If the attractive field is brought right down to a zero value in this way, as at the summit of the little hill to which he refers, the condition will have become stable, and the current will not increase further even though it has not reached its saturation value, unless conditions are changed by increasing the potential of the anode so that more current has to flow to counterbalance the increased attraction. This is the main effect responsible for the form of the characteristics of a high-vacuum valve, and it holds even when the applied voltages are such that the velocity of emission of the electrons is quite negligible. Professor Howe's account is a true explanation of the origin of the parts of the characteristic curve nearest the foot, where the currents are so small that the field due to the space-charge is unimportant compared with the velocities of emission. The anode voltage is then so low that the reverse slope of the little hill extends right out to the anode, and the space-current consists of those few electrons which start with sufficient speed to surmount it. As he says, there are some to which a potential difference of 4 or 5 volts does not present an unsurmountable obstacle.

The impression which the model has given to Mr. Pletts is not at all incorrect. In actual fact it is very common for a grid current of 1 micro-ampere to correspond to an anode current of 1 milliampere, a state of affairs where only one electron in a thousand does succeed in reaching the grid.

The bulk of Mr. Scott-Taggart's remarks, though interesting, concerns recent work which I have had to consider outside the scope of the paper. I agree that filament-springing is a very important point in small valves, and we cannot be content until a solution has been found as satisfactory as the normal practice in metal-filament lamps, in some of which the filaments are very much finer than those at present used in valves. The system adopted in the V24 valve is unsatisfactory owing to the loading of the free end of the spring with a sprung mass far greater than that of the filament to be supported; this results in transverse strains on the filament of a type which it is peculiarly unfitted to withstand. The small diameter of the R5 grid favours the short, steep characteristic which enables that valve to work on a 4-volt filament accumulator, an advantage which certainly had to be bought at a price. By a suitable readjustment of the grid spacing the amplification factor can always be restored to the desired value after a change in the grid diameter. In interpreting "backlash" observations as indicating the degree of evacuation it must be borne in mind that the electronic component of the grid current decreases as the grid is made negative far more rapidly than the positive ionic component which bears a roughly constant proportion to the anode current. Mr. Scott-Taggart's criticism would therefore apply only to observations on that side of the maximum of reverse grid current on which the electronic component is gaining on the ionic, and specifications must be so drafted as to rule out such observations. Rectification at the grid of a high-vacuum triode is considered in the paper in the paragraphs preceding and following Fig. 15. For the less common case of rectification at the lower corner of the anode curve (Fig. 22, curve 6), the physical principles involved are the same; the statement as to the fixity of the form of the curve below the 20-micro-ampere point applies to grid and anode curves alike. The upper corner of the anode curve can be treated, though somewhat roughly, by the method illustrated in Fig. 30; but the treatment for the rectifying property, while fully as cumbrous as that for the amplifying, is more seriously affected by the imperfect or gradual saturation which occurs in practice. As regards the grid characteristics of soft valves, however, I share Mr. Scott-Taggart's disappointment. The difficulty here is that one can by no means neglect the probability that a given ion, after missing one grid wire, will ultimately strike another and so make a contribution to the grid current, and yet this probability would be extremely difficult to compute.

The whole field of valve research at the present time seems to be strewn with cases of discovery and rediscovery such as that of the formula for the voltage factor or amplification constant remarked upon by Dr. Eccles. Captain Round mentions another. I have always understood that Sir J. J. Thomson's expression is obtainable by a method similar to that employed by Maxwell for the plane case, but is actually simpler owing to the higher symmetry of the cylindrical arrangement of the electrodes.

The neutralization of the space-charge, as the term is used in the paper, is a matter of electrostatics, or "pith-ball electricity," rather than, as some of Mr. Dowsett's remarks seem to imply, of the inner physics of the atom. It is effected, not by any close contact of positive and negative ions, but by the interpenetration of a cloud of negative electrons by a cloud of positive ions. Taking the simple case of an ion situated between two electrons,

the presence of a positive charge so placed will necessarily reduce the repulsion between the two negatives, i.e. will tend to "neutralize the space-charge."

Captain Round's summary criticism of the ultra-audion circuit carries one back in a flash to the days when most circuits merited a similar description. Nevertheless they did work in their several ways. It may fairly be contended, however, that the severe simplicity, both theoretical and practical, of the circuit of Fig. 5 was the result of intelligent pruning rather than improvised patchings. The question of the reliability at radio frequencies of statically determined characteristics is a matter of present-day interest and worthy of special research. It is perhaps because the available evidence is somewhat indirect that Captain Round sets his limiting frequency for the hard valve so low as 50,000 $\sim$ per second. He no doubt knows of many cases like that of the simple Lieben circuit of Fig. 1 in which variations of the resistance of the oscillation circuit agree with the corresponding variations in the critical slope of the characteristic with some approach to numerical accuracy at much higher frequencies. Again, observations of correlation between statical characteristics and circuit performances on the lines of Fig. 33, but relating to radio frequencies, are available. However, the question has never been thoroughly answered, and in some minds the characteristics are still suspect. Considering the internal physics of the valve, I am inclined to go very much further than Captain Round. With one exception, the various phenomena which it is necessary to take into consideration in accounting for the characteristics of low-voltage valves are instantaneous in comparison with periods longer than the very brief time of flight of an electron across the valve. The exception is the contact potential. This is dependent on the condition of the electrode surfaces, and the formation of surface layers is not instantaneous. But on following up Captain Round's query as to the soft valve one finds a very different story. The time of flight of an electron between plane electrodes 5 mm. apart and at 50 volts potential difference is 2×10^{-9} second, which is the time-period of a cycle at a wave-length of only $\frac{2}{3}$ metre. The movement of the positive component of the space curent will, however, be much more sluggish for positive ions are thousands of times heavier than electrons, and for atomic hydrogen, helium, and mercury respectively the critical wave-lengths will be in the proportion of 30, 60, and 400 on the same scale as before, the time of flight when, as here, the forces are equal, being proportional to the square roots of the masses. As the positive ions cannot be allowed as much as a full cycle for their motion, the effects of their slowness may well become pronounced at wave-lengths of 150, 300 and 1,000 metres for the three gases mentioned, and it should therefore be possible to observe differences between valves filled with equivalent atmospheres of helium and mercury. The effect on the characteristics of a proportion of positive ions sufficient to produce neutralization of the negative space-charge is certainly very pronounced, although their direct contribution to the total space current may be quite negligible, and it is possible that there is little further advantage to be gained by producing ions and electrons from the gas in number comparable with the primary electrons emitted from the filament. Figs. 18 and 6 (*a*) illustrate the two cases. The reverse grid-current shows approximately the number of positive ions and the corresponding anode current shows the number of electrons. The secondary electrons from the gas will be equal in number to the positive ions, and it will be seen that in Fig. 6 (*a*), where the saturated emission from the filament is only about 200 micro-amperes, they make a contribution of one-third to the anode current, whereas in Fig. 18 they are relatively negligible.

Soft valves are in general better rectifiers than the corresponding hard valves. For amplifying purposes it would certainly be possible, and indeed it would be no novelty, to make a reliable soft valve having the characteristics of Captain Round's four-electrode valve. Incidentally, might not this latter be called a "tetrode" according to Dr. Eccles's euphonious nomenclature?

On what evidence the internal capacities of soft valves when working are expected to be high I do not know, but some soft valves were included in the determinations mentioned at the end of Section 8, and showed a particularly marked decrease in the effective capacity between their electrodes on incandescing the filament. In making such observations it is essential to ensure that the effect is not masked by any increase in the damping of the resonant circuit, and, in the light of this discussion, not to employ frequencies too high for the positive ions to follow.

As regards the relations between characteristics and circuits I regret that I am unable to add to what has already been written on this subject. Systematic work on the verification of these relations was not undertaken until late in the period considered, and naturally so, because it does in fact represent a climax both in valve making and in the study of circuits, requiring, on the one hand, a sufficient selection of suitable valves, and, on the other, access to sufficient information as to the true action of the circuits in which they are used.

As long, however, as the terminals of the valve are so many boundary posts between the students of its internal action on the one hand and those of its external capabilities on the other, so long will the characteristics be the accustomed meeting-point of the two schools.

APPLICATIONS OF ELECTRICAL POWER ON MODERN GAS UNDERTAKINGS.*

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SUMMARY.

Preface.
Introduction of electrical power.
Charging and discharging machines.
" De Brouwer " projector machine.
" Fiddes-Aldridge " standard simultaneous stoking machine.
New type of " Fiddes-Aldridge " machine.
Early electrically-operated stoking machines: " Paris " turbine charger; " Oerlikon," " Bertrand " and " Sarraine " machines; " Lyons " machines; discharging machines.
Telphers.
Cranes.
Exhausters.
Rotary washers and pumps.
Gas boosters.
Blast fans.
Typical English installation.
Generating plants.
Waste-heat installations.
" Thomas " meter.
Conclusion.

PREFACE.

Practically every branch of the engineering trades has, during the past few years, opened its doors to the electrical system of power application, quite irrespective of whether such trades were or were not, either directly or indirectly, in competition with the electrical industry.

Amongst a host of other purposes electrical power has been extensively adopted for the operation of the various units of plant on the works of the principal gas undertakings in this country, on the Continent, and in the United States of America. In view of the special conditions which have to be catered for in connection with such plants, there are few purposes for which the electric motor is more admirably adapted, and no greater compliment has ever been paid to it on the ground of reliability than that implied by the readiness with which gas engineers have adopted it for driving their most important units of plant.

In the past, and to a certain extent at the present time, there has been, and is, an unfortunate tendency on the part of gas-undertaking officials to treat the fact that they themselves are users of electric power as a great secret, and to admit it only in a shamefaced apologetic sort of manner. Such an attitude, in the author's opinion, is wholly illogical and indicates a lack of confidence in one's convictions. Indeed, the progressive gas engineer has no cause whatever to be ashamed of the fact that he uses electrical power on his works, nor need he fear that by so doing he is playing into the hands of his competitors. Living in a progressive age, his training and experience teach him that " the old order changeth, yielding place to new," and he uses that power which his knowledge of modern methods convinces him will best meet his particular requirements. In short, he simply justifies his claim to the title of an engineer in the true sense of the word: " One who, by the judicious selection and the intelligent application of the forces of Nature achieves a given object with the least expenditure of energy."

By introducing electrical power on a large scale into his works the gas engineer demonstrates his acquaintance with the subject of the economical distribution of power and of those principles by which power, converted to a suitable form, may be economically applied over a wide area.

The question has been raised whether it is a wise policy for an undertaking in active competition with an electrical supply authority to introduce electrical power into its own works processes, and there are to-day gas undertakings on which the works power costs are kept unduly high by the unfortunate deference on the part of those in authority to this prejudiced and wholly illogical view. Such a policy is manifestly unfair both to the shareholders and the consumers of the undertaking pursuing it, and is against the interests of the gas industry as a whole. Incidentally the only body which is ever likely to benefit by it is the competing electric supply authority.

A still more absurd phase of the question is to be found in works which go to the expense of installing the most modern type of stoking and handling plant, and then, in fanatical adherence to such old-time prejudices, handicap that plant from its start by the application of some other form of power motors to machines which were expressly designed for electrical operation and which in this manner are rendered inefficient, costly to maintain, unreliable and, in some instances, distinctly dangerous.

INTRODUCTION OF ELECTRICAL POWER.

In the majority of works using electrical power the installation of an electrically-operated stoking machine (of the " De Brouwer " type in the case of most of the earlier installations) indicated the necessity for using a certain amount of electrical power, and from such small beginnings have sprung the large plants which to-day generate perhaps half a million B.O.T. units per annum in even a moderate-sized provincial works, solely for use on the various units of gas-manufacturing plant.

No unit of plant in the equipment of the modern

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gas-works has made such rapid strides into favour during the past 10 or 15 years as has the electrically-operated stoking machine whose advent has largely been the means of sweeping away old prejudices and conservatisms and of marking the commencement of a new era in gas-works practice.

The electric driving of machinery has been described as one of those methods the advantages of which always turn out to be greater than anticipated, owing to the fact that the benefits which accrue to the power user by their adoption are made up of a number of small conveniences and time-savings which are difficult to enumerate effectively.

It is generally recognized that the first steps towards economy and efficiency in working in all industries lie in the abolition of isolated power plants, which are scattered about a works (particularly where such plants are steam-driven), and the production in bulk of all the power required at a centrally-situated power house from which it could be economically distributed to those points at which a demand for power existed.

A modern gas-works, with its many power-using units of plant scattered over a wide area, offers ideal facilities for the practical demonstration of this principle, the soundness of which, within the last 10 years, has been realized by a large number of gas undertakings after what can only be described as a period of stagnation. The lethargy of gas officials in respect to their works power-costs may have been largely due to conservatism, but it can also be accounted for in the following manner :

On all gas-works a continuous supply of steam is essential for the processes of coal-gas and water-gas manufacture, and for the operation of the chemical process plants which are to be found on all works of any size. These requirements naturally lead to the necessity of keeping a considerable amount of boiler plant in commission, and the ample supply of steam which is thus available accounts for the large number of single-cylinder non-condensing steam engines and pumps which up to a short time ago were to be found scattered about the works of most undertakings.

Supplied with steam from an arterial system of mains running all over the works, through draughty stores and inaccessible places, the pipes often being unlagged, such engines, of course, were wildly extravagant, using very probably something like 100 lb. of steam per b h.p.-hour ; but in spite of their drawbacks they were reliable, and this is the sole reason which can be advanced for their continued employment.

It must be explained that, consequent upon the development of labour-saving machinery, there are now a far greater number of points on a gas-works at which a demand for power exists than there were, say, 10 or 15 years ago, and when an attempt was made to meet such growing demands by this type of engine it was found that additional boiler power would have to be laid down or an entire change made.

As has already been mentioned, the installation of an electrically-operated stoking plant together with perhaps a small telpherage led, in the majority of cases, to the employment of electrical power, generated usually by means of a gas engine and dynamo of just sufficient capacity to meet the demands of the new plant. After this, however, it is a fact that electricity was often looked upon as a necessary evil, necessary because of the use of an electrically-operated stoking machine for which power had to be provided, and for a long time no effort was made to utilize it in other directions until the increasing demands of the steam-eaters (to which allusion has already been made) indicated the necessity of installing additional boiler power or of using the existing steam supply in a more economical manner.

The situation thus created, helped perhaps by the persistence of contracting firms in pressing the claims of the electric motor when tendering for new plant, resulted in a broader and more reasonable view being taken of the whole subject of electrical power application, and gas engineers, realizing its many conveniences and economies, applied this form of power, with very few exceptions, for the operation of all units of their plant.

In connection with the earlier installations on gas undertakings it must be confessed that the responsible engineers had a very rudimentary knowledge of electrical science and, in consequence, the general type of plant laid down was in a great measure left in the hands of the contractors who were supplying the machinery for which electricity was required. Their interests, naturally enough, did not extend beyond the particular machinery for which they were contracting, and the plant installed was rated more or less upon the demand created by that machinery. Had a contractor ventured to suggest that generating plant of a higher rating be installed, with a view to future demands coming on it, there is no doubt that his reception would have been the reverse of cordial. Thus, there is little doubt that the contractors did their best, and things, on the whole, went very well, except that in most cases, owing to the poorness of the load factor (equivalent to that of a crane installation in the earlier gas-works plants) the plant did not operate with that degree of efficiency which a new order of things has brought about.

It was only when the question of extending the scope of the electrical plant came up for consideration that the limitations of the existing generating sets became apparent, and where new plant had to be installed it was usually rated upon the basis of all those purposes for which it had become apparent that electricity could advantageously be applied.

Later in this paper the author proposes to deal with the low rate at which steam can be raised on most gas undertakings. In some cases when it came to the question of installing new and larger generating sets it was found advantageous to abandon the small gas-driven sets which had carried the works through the first stage, and to install high-speed engines of the Bellis type supplied with steam raised by the burning of low-grade fuel, namely coke-breeze, which on most gas-works is a drug in the market but makes a very good steam-raising fuel if burnt under proper conditions. One of the most curious facts in connection with the development of electrical driving on gas-works is the time that in most cases elapsed between the initial installation of a small set for working a stoking machine and the extended application of this power to the many other units of plant.

The last decade has sounded the knell of the single-cylinder steam engine so largely used on gas undertakings, and, unit by unit, most of the plant on many of our large works has been turned over to electric driving.

To a great extent, however, gas engineers have, wisely on the whole, resisted the temptation to throw out well-maintained and valuable units of plant simply because it was considered that thay were not adapted for electrical driving. In some instances in which the change-over from a gas or steam engine to an electric motor has not been successful this is the explanation that has been advanced, but the author's experience shows that the only way to ensure a satisfactory job is for the responsible engineer to possess intimate knowledge, not only of the electrical side of the question, but of the characteristics of the plant he is modernizing and of the conditions under which it operates. Under-rating, unsuitable selection of motors and control gear, and ignorance of the conditions which have to be fulfilled, are responsible for 95 per cent of such failures.

Generally speaking, units of plant which for years have been run satisfactorily by either a steam or a gas engine, will run just as well, and probably better, when motor driven, always provided that the man who carries out the alteration understands both ends of the plant thoroughly. One of the most interesting aspects of the work of an engineer who is engaged in a modernizing programme is the scope which exists for the exercise of ingenuity in adapting old but reliable plant for working under newer conditions and in carrying out such alterations with a minimum of delay. In many units of plant modernized in this manner by the author *one day* was the maximum time during which that plant could be spared out of commission.

Amongst the purposes for which electrical power is to-day employed on an up-to-date gas undertaking are the following :—

Charging machines.	Agitators.
Discharging machines.	Hydro extractors.
Conveyors.	Air compressors.
Elevators.	Electro-tinning plants.
Exhausters.	Machine tools.
Gas compressors.	Woodworking tools.
Disintegrators.	Blowing fans.
Washers.	Boosting fans.
Cranes.	Hoists.
Telphers.	Pumps.

The author proposes to deal with those of the above applications which he has reason to think may be of interest to the members.

Charging and Discharging Machines.

Under this heading fall the most interesting units of plant on the entire works, but before going into the question of development and type of the various stoking machines it may not be out of place to devote a little time to a description of those requirements which render the use of such machines necessary.

For the benefit of those who may not be familiar with the interior of a retort house the section in Fig. 1 has been prepared. This is a section through a modern five-tier retort house of the horizontal type. For some years opinion in the gas industry has been divided as to the respective merits of the vertical and the horizontal type of retort-setting, each type of plant having its own adherents. Had it not been for the development of the stoking machine for the charging and discharging of horizontal retorts, there is little doubt that this class of setting could not have survived, but with modern charging and discharging machines which allow of heavy charges being worked the horizontal setting more than holds its own, and in the United States has been developed on a scale never attempted in England.

No further mention will be made in this paper of the vertical retort installation, as this type does not necessitate the use of any type of machine which is not included in the above list.

In a modern retort-house installation the brickwork setting in which the retorts are installed is built longitudinally through the centre of the house, the space between the sides of the setting and the walls of the house being known as the charging and discharging stages respectively. These stages are on about the level of the top of the regenerative furnace under the retorts, and about a foot below the level of the floor of the bottom retort.

In the case of a typical modern English installation each setting consists of 10 retorts each 20 feet long having a deep-sided D-section arranged in two vertical tiers of five. Each end of the vertical retort is fastened into a cast-iron mouthpiece of similar section, which is furnished with a sealing door, making a gastight and airtight joint. The gas freed during the process of distillation within the retort passes through an outlet cast in the mouthpiece, and rises through ascension pipes to a common main running longitudinally above the setting. The gas passes into this main via a water seal, each ascension pipe terminating in a dip pipe whose end is sealed under the surface of the liquor in this main, which is generally known as the hydraulic main. These seals act as non-return valves, and prevent gas from the hydraulic main escaping through the mouthpiece when the retorts are opened for charging or repairs.

Each setting of 10 retorts has its own coke-fired regenerative furnace situated at the foot of the setting, by which means the retorts are maintained at a uniform temperature of about 2,000° F. The products of combustion from these furnaces after heating the retorts pass into a common main flue running the whole length of the settings.

By means of exhausting machinery placed exterior to the retort house the interior of the hydraulic main is maintained in a state of slight vacuum, and under the influence of the "pull" so exerted the gases freed from the coal during the process of distillation are drawn forward out of the retort house in the direction of the purifying plant.

An installation of horizontal retorts capable of carbonizing, say, 150 tons of coal per day would consist of 10 settings of the type described built in a continuous line, the total number of retorts being 100.

These retorts would be charged twice a day with 14–15 cwts. of coal after the incandescent coke product from the previous charge had been ejected by the discharging machine. When it is recognized that such a house working at its full capacity necessitates the handling of 150 tons of coal and about 100 tons of incandescent coke per 24 hours, the necessity for the employment of some form of efficient stoking machinery becomes obvious. With hand-stoking such charges and such settings as those described above would be out of the question, and for an equal output a much larger number of retorts built into a very different class of setting would be essential, while the area covered by the plant would be much greater in the case of the hand-stoked house.

In a modern house the charging stage shown in Fig. 1 usually of such capacity as to hold sufficient coal for 16 to 20 hours' working. From time to time the charging machine runs under these bins and replenishes its own hopper.

Where, however, a large number of settings have to be dealt with and a high rate of stoking speed is necessary to enable the machine or machines to get over the ground in proper time, a continuous line of coal bins is installed over the charging stage, each one fitted on its underside with a sliding door. Stop-plungers are fitted on the upper part of the charging machine which, when in the raised position, engage with opening levers on these sliding doors. The travelling machine, with its stops raised, automatically opens the hopper door and allows a charge of coal to pass from the storage bins to its own hopper. After taking in a charge in this

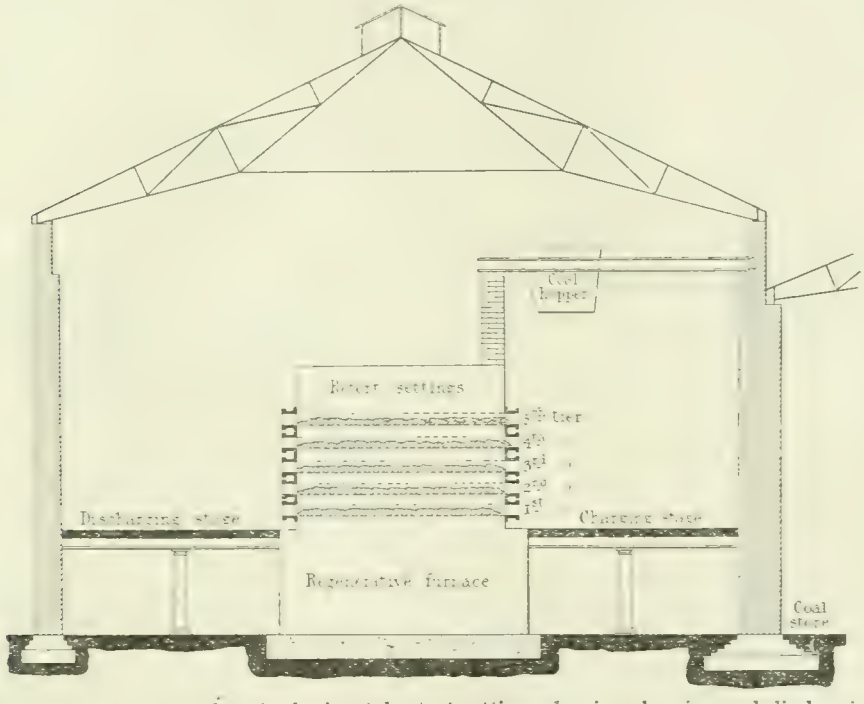

FIG. 1.—Section of modern five-tier horizontal retort setting, showing charging and discharging stages.

accommodates the discharging as well as the charging machine, both being run on the same set of rails. In many of the older installations rake machines for discharging the coke were held in great favour, but of late years, due to the evenness of the charge put in by a modern machine, it has been found possible and advantageous to abandon the rake machine in favour of the ram or pusher type.

Whatever their type, the charging machines are invariably fitted with a coal hopper of a capacity depending upon the size of the installation and the speed at which it is necessary to work. In the case of a small number of settings where a good speed of working is not essential the hopper on the machine is kept supplied with coal by one or two bins set in a convenient position above the charging stage as shown in Fig. 1. These are kept filled with coal by an elevator or elevators and are

manner further movement of the machine results in the closing of the hopper doors so that it is impossible for a machine to pass from underneath a storage hopper and leave the same open.

The only machinery installed on the discharging stage is either a hot coke conveyor or a telpherage for the purpose of taking charge of the hot coke as it is ejected from the retorts by the discharging machine and transporting it to the coke silos or storage bins. Where a water-gas plant is installed, a branch telpher track is sometimes employed for the purpose of transporting the hot coke direct from the retort house to the storage bins of the water-gas generators.

Before proceeding to discuss the different types of stoking machinery it will greatly simplify matters if it is explained that, however the operation of charging and discharging the retorts may be affected by the

various types of machines in use, they all have two common characteristics. In the first place they have to be capable of a longitudinal travel at a rate of about 100 feet per minute up and down the house in which the settings are installed. This requirement necessitates the stoking mechanism being carried within a wheeled base fitted with a travelling motor, control gear, and the necessary reduction gear for breaking the motor speed down to that required at the rail wheels. In the second place it is essential that the stoking mechanism should be capable of a vertical adjustment in order to enable it to deal with retorts at varying heights from the level of the stage. In the case of a five-tier setting the amount of vertical adjustment necessary is 8 feet. To meet this condition a high skeleton superstructure is erected on the wheeled travelling base, and inside this a platform or frame is suspended in such a manner as to be capable of being raised or lowered within the required limits by means of steel ropes or chains.

the essential portions of a De Brouwer projector. Within a suitable frame is accommodated an endless rubber belt about 15 inches in width, which runs over and between one large wheel (A), and three small pulleys, (B), (C) and (D). The pulley (B) also serves as a driving pulley, and is belt-coupled to a shunt-wound electric motor, by which means a speed varying between 1,100 and 2,200 ft. per minute is imparted to the belt. The large wheel (A), usually one metre in diameter, is cast with a large central groove in its periphery, and a spout or tundish fitted just over this groove provides a path for the coal from an overhead hopper down to the surface of the moving belt. The speed of the coal falling on to the belt is gradually increased, and finally attains the same velocity as the belt. When the latter turns downward over the pulley (B), the stream of coal flies off at a tangent, and in this manner it is projected into the retort which it is desired to fill. This stream, of course, bends down under the influence of gravity,

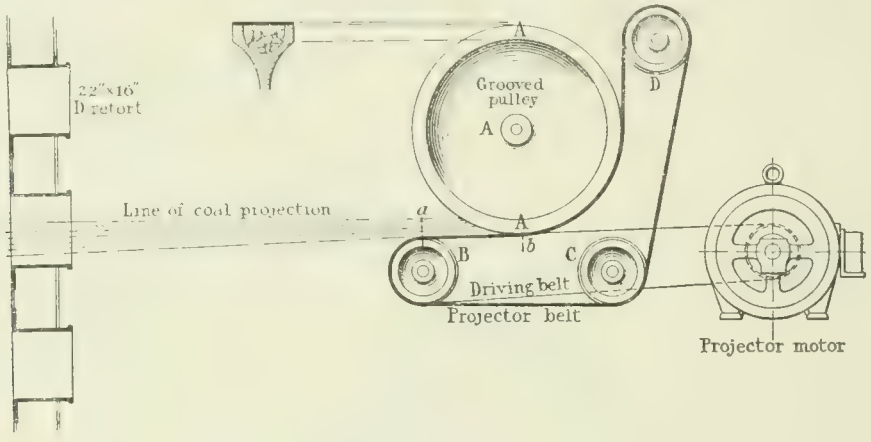

FIG. 2.—" De Brouwer " projector machine.

" DE BROUWER " PROJECTOR MACHINE.

Named after its inventor, M. De Brouwer, for some time engineer of the Bruges gas-works, the De Brouwer projector machine has the distinction of being the simplest and most efficient device ever designed for filling a retort with coal. Following upon its introduction into the Bruges gas-works, nearly 20 years ago, it was speedily adopted in every gas-works of any size in Belgium. It is a significant fact that although this machine has been exploited since 1903 by a particularly live firm of English engineers, the resultant years of accumulated experience have not warranted any radical departure from M. De Brouwer's original design, and the machines now being produced at Messrs. W. J. Jenkins' shops at Retford are to-day, so far as the actual projector mechanism is concerned, identical with the machine which, in 1902, proved its worth in the retort house at Bruges.

As its name implies, the " De Brouwer " is a projector machine, no portion of its mechanism entering the retort to be charged. The coal is projected from the machine in a manner similar to that in which water leaves a hose-pipe. The principle of the machine will be readily grasped by reference to Fig. 2, which shows

and by varying the speed of the belt (and hence the velocity of the coal) by shunt regulation, an even layer of any desired thickness is deposited on the floor of the retort.

An obstruction, in the form of a stop plate, is placed in the far end of the retort, and the energy in the coal is finally dissipated, partly by shock in coming into contact with this stop, and partly by lifting the coal to a certain height in opposition to gravity. This height gives the required thickness to the charge. So long as the initial speed and the sliding friction remain the same the layer will be of even thickness, but if either of these factors be varied, there will be a corresponding alteration in the thickness of the charge. By gradually slowing down the speed of the projector belt-motor and so reducing the velocity of the projected stream of coal, an even layer can be laid throughout the length of the retort. The whole operation of charging a 20-ft. through retort takes from 25 to 30 seconds. In order to meet the conditions in a modern retort house, the projector mechanism is suspended within a motor-driven travelling frame. The motor installed for propelling the machine up and down the house also serves the mechanism which raises and lowers the projector

according to the height of the retorts which it is desired to charge.

In practice it is found that a De Brouwer band will handle about 18,000 tons of coal before it becomes necessary to renew it. These machines are built in three types, namely, the projector machine; the ram machine, which consists of a telescopic ram installed, like the projector, in a wheeled base; and the complete stoking machine, which combines within one frame both the above-mentioned mechanisms.

"Fiddes-Aldridge" Stoking Machine.

The Fiddes-Aldridge stoking machine manufactured by Messrs. Aldridge and Ranken is the only purely simultaneous stoking machine used in English gas-works. By the term "simultaneous" is meant a machine which performs the operations of discharging the hot coke and introducing the fresh charge of coal into the retort simultaneously.

The actual stoking mechanism is shown very clearly in Fig. 3, and consists of a series of box-shaped links joined together in such a manner as to permit them, when withdrawn from the retort, being accommodated around the periphery of a polygonal wheel, which also serves the purpose of driving the chain into, and withdrawing it from, the retort. On each side of each link a driving block is fixed in such a position as to engage with pairs of driving arms bolted on the sides of the chain wheel. By means of suitable gearing the chain wheel is caused to rotate very slowly and, the projecting driving arms engaging with the blocks fitted on the sides of each link, the chain is driven forward out of the machine into the retort in which it is extended as a solid trough. The trough so formed has no bottom, but the sides of each link are held rigidly together by means of arch stays as shown in the details of the chain. The trailing end of the last link is anchored to the chain wheel. The front of the first link or nose is masked by means of a steel door suspended from the hood which arches over the front link. When hanging in the vertical plane this door completely covers the end of the chain but is free to swing outwards and upwards on its hinge.

The method of operation is as follows:—The machine having been adjusted in front of the retort to be stoked the chain is slowly driven out of the machine into the retort and at the same time a charge of fresh coal is allowed to fall from an overhead hopper into the slowly moving chain. A drop-apron plate falling from the front of the machine forms a bridge between the latter and the mouthpiece of the retort. The chain receives its charge of coal just as it passes out of the machine on to this apron plate. The masked end of the front link or nosepiece on meeting the caked coke acts as a ram and the carbonized mass is pushed out of the retort.

When the chain is known to have travelled right through the retort the mechanism is stopped and the chain comes to a standstill in the discharged retort with its interior filled with the fresh charge of coal up to the level of the arch stays. Upon the reversal of the stoking motor the chain commences to travel back into the machine and, as soon as it commences to move, the inside face of the masking door at the front of the chain meets the end of the charge lying in the trough formed by the two sides of the chain and, being free to open, further movement of the chain causes this door to swing upwards and to trail over the top of the charge. The adhesive friction of the charge on the floor of the retort prevents the coal being drawn back and the two sides of the chain links slide back past the coal into the machine, leaving the charge lying loosely on the bottom of the retort.

In order to ensure that the coal moves forward into the retort evenly with the chain, a number of push-plates are suspended from the arch stays. These push-plates, while free to trail over the top of the charge on the return stroke of the chain, are so fitted as to form a rigid partition every couple of feet in the chain during the forward stroke. In this manner a charge of 10–11 cwts. of coal can be laid loosely and evenly in a 22 in. × 16 in. × 20 ft. through retort by the same operation which expels a charge of 6–7 cwts. of incandescent coke.

The speed of the chain through the retort is about 70 ft. per minute, and the dual operation of charging and discharging occupies from 50 to 60 seconds.

The machine shown in the illustration is a standard machine fitted with a stop plate which has been recently introduced with a view to increasing the charge. This gear consists of a plate which follows up behind the charge into the retort and is maintained in position until the chain is completely out of the retort, after which it is drawn back into the machine. By its use it is possible to fill the chain to its maximum capacity without having to allow for the slight longitudinal spreading out of the charge which takes place upon the withdrawal of the chain past the coal deposited in the retort.

The standard Fiddes-Aldridge machine, as manufactured up to about 1915, was a single-motor machine, the three motions being picked up by means of heavy dog clutches. These took an appreciable time to operate, and the best working of which the machine was capable was one retort completely stoked in 65 to 70 seconds. After that date a separate motor was used for the travelling mechanism as a result of experiments carried out by the author, and it was found that the machine modified in this manner was capable of completely stoking a retort in from 45 to 50 seconds. Apart from the increased number of settings with which a one-machine installation was capable of dealing, it was found that a considerable saving of gas took place owing to the rapidity with which the machines could move up to, and away from, an open retort. The shorter period during which the retort mouthpieces were open resulted in conservation in heat, and a diminution in the amount of lost gas, and on an undertaking carbonizing about 60,000 tons of coal per year the saving thus effected represented from 2,500 to 3,000 tons per annum.

As a result of a series of tests it was found that the electrical energy consumed per completely stoked retort amounted to 0·093 B.O.T. unit, or 0·23 B.O.T. unit per ton of coal carbonized. These figures include the power used for ejecting the hot coke from the retorts.

New Type of Fiddes-Aldridge Machine.

The original Fiddes-Aldridge machine was developed at a time when comparatively light charges were still favoured by most gas engineers, and one of its few disadvantages lay in its inability to compete with those machines which were especially designed with the object of practically filling the retort. The use of the stop plate and continued refinements in the design of the chain have enabled it to place substantially heavier charges in the retorts than was at first possible, but in spite of these improvements the fact remains that a certain percentage of the capacity of the retort has to be reserved for the accommodation of the chain during its brief sojourn in the retort, and it is consequently impossible to fill a retort completely with this type of charging mechanism.

In order to meet the demand for a machine to put in

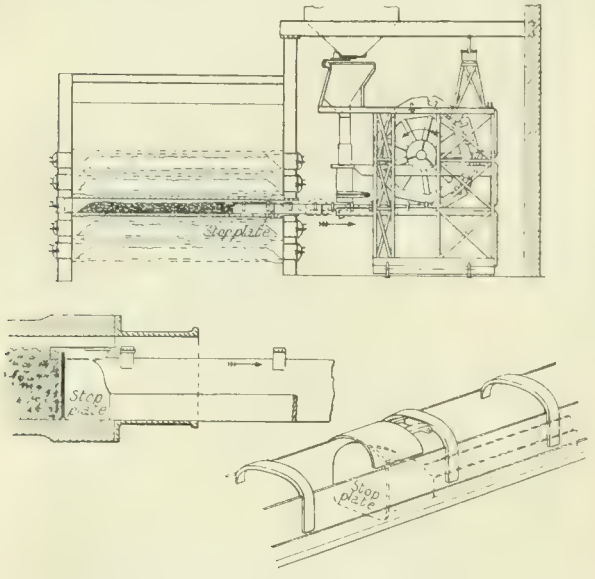

Fig. 3.—Standard " Fiddes-Aldridge " stoking mechanism.

the heavy charges so favoured by present-day gas engineers an entirely new type of machine has been developed, and during the past three years has been subjected to exhaustive tests at the Beckton works of the London Gas Light and Coke Company.

A sectional view of this machine is shown in Fig. 4, which represents the stoking element being withdrawn from the retort. At the foot of the illustration two enlarged views of the end of this mechanism are shown. It will be seen that the machine is built on the same general lines as the standard machine illustrated in Fig. 3, the polygonal wheel being retained for the purpose of working a special form of chain into and out of the retort. The great difference between this machine and its predecessors lies in the chain itself and in the method by which the charge of coal is introduced into the retort. Instead of this chain forming a hollow trough for the reception of the fresh charge of coal on its journey into the retort, a small-slat conveyor is accommodated between the two sides of the chain, the path of this conveyor being shown in the figure by dotted lines. The enlarged sketch at the bottom of the illustration shows one end of this conveyor situated within the nose link of the chain.

When withdrawn into the machine the main chain, conveyor and all, is accommodated around the periphery of the polygonal wheel, the necessary adjustment between the centres of the conveyor being provided for by powerful tension springs by means of which the driving end of this small conveyor is anchored to the chain wheel. The latter wheel is mounted on two very heavy short-stub axles, one on each side, and the driving shaft for the operation of the conveyor is carried through the centres of these stub axles. By means of a suitable clutch gear adjacent to the operator the conveyor can be put into operation at will. The method of stoking a retort is as follows:—The machine having been adjusted in front of the retort to be dealt with, the chain is driven forward in the usual manner and is used simply as a ram during the forward stroke. After it has travelled right through the retort the operator

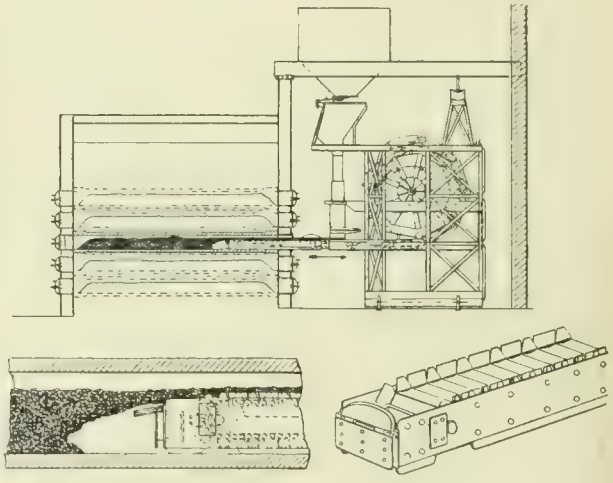

Fig. 4.—" Fiddes-Aldridge " new " A " chain machine.

reverses his motor and at the same time operates the clutch which gives motion to the conveyor. This commences to run at a speed of about 600 feet per minute, the direction being such that the top portion of the conveyor is running into the retort when the chain itself is being withdrawn. Simultaneously with the reversal of the chain a stream of coal is automatically released from the machine hopper and falls on to the now rapidly moving chain which carries it forward into the retort and deposits it over the nose of the chain in a loose-lying and even layer. Certain initial difficulties were encountered in the manufacture of a chain capable of standing up to the necessarily severe conditions which this service imposes, but these are being rapidly overcome, and there is no doubt that this machine will soon take its stand at the head of English stoking machines.

It will be noted in this new machine that the much-desired " simultaneous " characteristic is retained and that the evenness and general disposition of the charge in the retort is entirely independent of the human

element, the ratio between the speed of the conveyor and the chain being unalterable. In spite of the large charge which the machine puts in, no difficulty whatever is experienced in pushing it out, as would be the case if a Fiddes-Aldridge machine were used to discharge a retort which had been filled by a projector machine. This is due to the fact that the high velocity with which the charge from a projector machine enters the retort causes the particles of that charge to enter into the closest association with every crevice and irregularity in the retort. In the case of the new Fiddes-Aldridge machine the charge is gently deposited on the floor of the retort and lies very loosely; consequently it does not require so large a pushing effort to discharge it when the process of carbonization is completed as would be the case with a projected charge.

Early Electrically-operated Stoking Machines.

Up to about 18 years ago no appreciable progress had been made in this country in the development of electrically-operated stoking machinery, due, in all probability, to the fact that the then requirements of the English gas industry were excellently catered for by the West pneumatic and the Arrol-Foulis hydraulic charging and discharging machines. At that time both these types were well established in English gas-works and were held in high esteem. Even up to a short time ago both the West and the Arrol-Foulis machines were formidable rivals to the electrically-operated stoking machines, and many engineers at the present time regard the Arrol-Foulis as the best machine for discharging work.

On the Continent, however, much attention seems to have been given about this time to the application of electricity for the operation of stoking machinery, and during the period 1901–1903 no less than four different types of plant were brought to the notice of gas engineers, namely, the De Brouwer projector machine, the Paris turbine charger, the Oerlikon and Bertrand chargers and dischargers, and the Sarraine machines, as well as a special type of charging machine developed at the works of the Lyons Gas Company.

At this point attention may be drawn to the coincidence whereby two men, strangers to each other and of different nationalities, were both working towards a desired end along somewhat parallel lines and both relying upon centrifugal force. Thus while in 1902 M. De Brouwer was perfecting his projector machine at Bruges in Belgium, so at the Villette works of the Paris Gas Company other engineers were engaged in the development of the turbine charger, which eventually threatened to hold the field against all comers until it became realized that the simplicity of the De Brouwer machine did not detract in any way from its reliability and durability.

The "Paris" Turbine Charger.

This machine, developed at the Villette works of the Paris Gas Company and subsequently introduced into a number of Continental works as well as into the Beckton works of the London Gas Light and Coke Company, consisted of a steel outer casing accommodating a variable-speed rotor driven by an electric motor. The function of this rotor, which somewhat resembled the paddle wheel of a steamer, was to impart such a degree of velocity to the particles of coal that were allowed to fall into the casing as would cause them to be projected into the retorts in a continuous stream. A coal hopper was installed above the turbine element and a motor-driven feeding appliance ensured a perfectly controlled stream of coal falling on to the rotor blades.

As in the case of the De Brouwer machine the speed of the motor was varied according to the disposition and depth of the charge it was desired to place into the retort, but the great difference between these two machines lay in the fact that, while in the De Brouwer projector the particles of coal were gradually accelerated to the required velocity with practically no shock, the "Paris" machine imparted this velocity to the charge only as a result of a series of collisions between the coal and the rapidly revolving rotor blades. The principle, however, on which this machine worked is still employed, and certain of the modern machines still use a form of centrifugal rotary projector somewhat similar to that on the "Paris" charger.

A particularly interesting feature of the "Paris" turbine charger lay in the fact that the required variation in the speed of the rotor was brought about automatically, thus rendering the actual formation of the charge in the retort independent of the human element. Curiously enough, the author at one time spent a considerable time working out a method by which the speed of a De Brouwer projector belt could be subjected to automatic variation, being quite unaware that a similar form of automatic control had been tried nearly 15 years before at the Villette gas-works.

The "Oerlikon," "Bertrand," and "Sarraine" Machines.

The charging mechanisms respectively employed on these machines, while differing largely in structural details and method of operation, consisted of a box-shaped scoop of a length slightly in excess of that of the retort which it was desired to charge. This scoop was constructed in longitudinal sections joined together in such a manner that although it was capable of being driven forward into the retort as a rigid element, it could be withdrawn one section at a time without disturbing or drawing back the charge of coal which it had carried forward into the retort. When the separate sections had been drawn back into the machine the scoop automatically resumed its rigid form in readiness for the next charging operation. The cycle of charging operations of these machines occupied about 60 seconds from retort to retort.

Having regard to the fact that the specifications of these early French machines were invariably accompanied by the specification of some form of motor-driven ram or rake machine for the purposes of discharging the retorts, it is obvious that they were primarily designed with a view to charging the retorts, but the fact remains that the Oerlikon, Bertrand and Sarraine machines possessed all the essentials of the "simultaneous" type, and, if the scoops had been sufficiently stiff in construction, could have been used

for pushing the coke out of through retorts by the simple expedient of masking the end of the scoop.

The "Lyons" Machines.

The machines installed at the Villeurbanne works of the Lyons Gas Company were of a special type and, while somewhat similar to the Oerlikon and the Sarraine machines in respect to the charging mechanism, were certainly much simpler. The portion of the machine which actually entered the retort consisted of a steel cartridge or tube built up on a suitable framework and split along its horizontal axis as shown in Fig. 5. The top and bottom halves were joined together so that

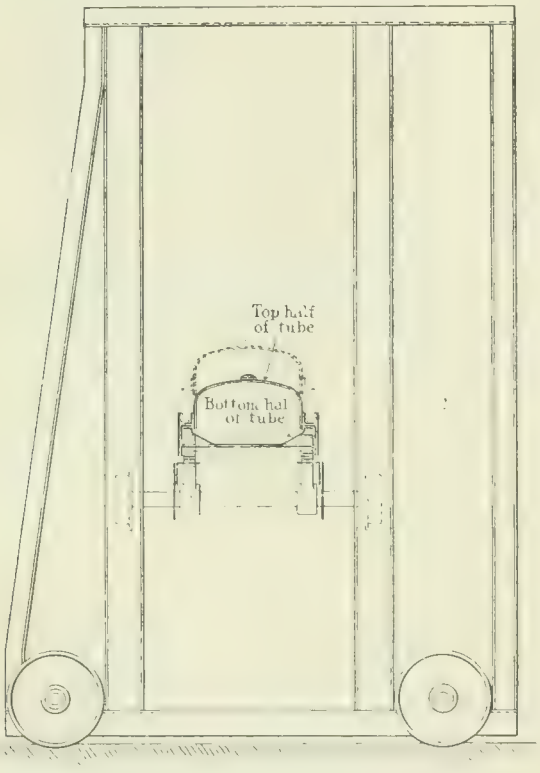

Fig. 5.—Section of cartridge charging mechanism of the "Lyons" machine.

the tube could be driven forward into the retort as a rigid element. On the return stroke, however, the two halves were dissociated from each other and could be drawn back independently and at varying speeds if desired. Thus the bottom half could be first drawn back into the machine, an arrangement of plates on the interior of the top half preventing the coal following the floor of the scoop, and then the top half could be withdrawn from the charged retort. By withdrawing the bottom half at a higher speed than the top the amount of the charge left in the retort could be regulated. The preliminary filling of this tube or scoop before entering the retort was accomplished by tilting it within the machine to an angle of about 50 degrees and then allowing the coal to gravitate into it from an overhead hopper.

In the foregoing description of the early French machines the author has confined his remarks to the actual charging elements. The methods by which these elements are operated in and out of the retorts consisted in the application of ordinary mechanical principles and are not of sufficient interest to warrant any detailed description.

It will be understood that all the above-mentioned machines were accommodated in an outer frame carried on a wheeled travelling base. Inside this frame the stoking mechanisms were free to rise and fall in order to adjust themselves to the different tiers of retorts. In some of these machines the inner frame was not suspended by wire ropes or chains but travelled up and down on a number of vertical square-threaded shafts, usually four. These square-threaded shafts were fitted with chain sprocket wheels at one end and were coupled by an endless chain. In some of these machines separate motors were installed for the operation of the travelling and vertical adjustment mechanisms; in others one motor served both these mechanisms through a suitable gear box and clutches.

Discharging Machines.

In connection with the charging machines which have been described, some form of pushing or drawing machine was obviously necessary for the purpose of discharging the burnt-off charge from the retort. The best method of discharging a retort either by pushing or drawing depends upon the character of the charge. A sectional charge, that is to say one put in by a number of operations, frequently piles up and forms an obstruction in the retort if an attempt is made to push it out, and drawing machines are usually used for the purposes of dealing with such charges. In the case of a projector charge or a charge which has been laid in the retort in one operation such difficulties are not encountered and the ram machine has been found to be quite satisfactory.

The use of a ram machine working on the same sets of rails as the charging machine confers a great advantage, inasmuch as no hot coke is handled on that side of the house which accommodates the stoking machines.

While differing in structural details, most of the earlier discharging machines were built on very much the same lines, the rotary motion of the motor being finally imparted to the ram or drawing element (as the case might be) by means of one or more sets of racks and pinions. The discharging mechanism was of course installed in a wheeled travelling base in which it was capable of the required amount of vertical adjustment. None of these older discharging machines is of sufficient interest to warrant any special description.

Telphers.

The mono-rail telpher is rapidly becoming a standard unit of plant on modern gas-works, and has done much to reduce the heavy handling charges with which, under the old regime, practically all gas undertakings were burdened.

Telpherage is admittedly not applicable to all retort houses on account of structural objections, but the efficient manner in which these installations are dealing with the hot coke discharged from the retorts of a large and increasing number of works is rendering the telpher a serious rival to all other forms of conveying plant for this purpose, in respect to both horizontal and vertical retort installations. Except in cases where the run between the retort house and the coke storage heap or bunkers is excessive, it will be found that a one-machine installation will deal with the discharged coke as quickly as one retort-discharging machine can push it out.

The usual practice is to push the hot coke direct from the retorts into lattice bar skips, three or four of which, at the commencement of the discharging round, are placed in readiness on the discharging stage in front of the benches to be dealt with. These skips, as they are filled, are lifted and conveyed in rotation from the retort house to the coke storage site, being quenched *en route* in the quenching tank. The telpher returning to the retort house deposits each empty skip again on the stage in advance of those already there, awaiting their turn to be filled. In this way the machine can do its work without loss of time or hindrance, and so keep up with the charging machine.

It is usual to carry the contents of two retorts in each skip load, but in some works where the charges are not very large the contents of three retorts can be handled each trip, about 25 to 30 cwts. of coke being the maximum quantity which can be conveniently quenched at one time.

After quenching, the coke may be conveyed either to the coke yard or to any point on the works at which a supply of coke may be required, such as the water-gas plant, batteries of boilers, or direct into railway trucks for shipment. For these purposes branch tracks are often installed running off the main retort house coke-yard loop; in this respect the ease with which the mono-rail telpher system lends itself to extension renders it particularly valuable on a growing works. By means of it coke may be conveyed over long distances with a minimum of handling and breakage, the consequent accumulations of breeze being reduced to a minimum. The skips are of heavy construction in order to withstand the varying condition of temperature and hard usage, and are so balanced as to be self-tipping when full, and automatically to right and lock themselves when empty. The tipping action is controlled by a following cord fitted with compensating gear in the driver's cab.

Apart from the simplicity and low running and maintenance costs of the mono-rail telpher, one of the chief advantages which renders it particularly suitable for the handling of hot coke lies in the fact that all its working parts are removed from the heat and the destructive action of coke dust, factors which are invariably responsible for heavy maintenance costs in connection with ordinary coke conveyors. Its use in the retort house allows the discharging stage to be kept clean and dry, and a great improvement to be effected in the arduous conditions under which retort-house men work.

Cranes.

In many modern installations the claims of the jib crane carried on a high gantry seem to have been ignored apparently for no other reason than that this well-proved method of handling is old fashioned. The dangers of modernity become very apparent in some instances in which elaborate conveyor or telpherage schemes have been installed for storage or stacking duties that could have been as efficiently and much more cheaply performed by a jib crane.

For transportation services which must be carried out at a high rate of speed and over comparatively long distances the mono-rail telpher is an ideal machine, but for storing or stacking the jib crane is able to cover a large area at a good height at a comparatively low capital cost and its claims are not so fully examined in connection with handling schemes as its advantages warrant.

The modern electrically-operated jib crane with its separate motor for each motion is a very efficient unit of plant and lends itself to a much higher rate of working than was possible with the more ancient steam crane. A travelling jib crane mounted on a suitable gantry has command over every square foot of the area which it serves, but this same advantage is not possessed by a telpher, which has command over only that portion of the ground lying immediately under its track. A certain amount of side swing takes place in regard to its grab, but this swing can be neither induced nor regulated by the driver.

Exhausters.

In spite of the extent to which, during the past few years, electricity has been adopted in connection with gas-works plant, it is significant that the cases in which it has been used for the driving of the main exhausters are few and far between. These exhausters have been aptly described as the "heart of a gas-works," and absolute and literal continuity of running is the first essential in connection with such machines. This requirement accounts for the continued employment of steam engines and, in the more modern plants, turbines for this purpose.

With steam-driven exhausters a throttle valve is connected to a gas governor, in such a manner as to vary the speed of the engine automatically in the event of any variations in the degree of partial vacuum which the exhauster exerts on the retort-house main. In the event of the vacuum falling, the engine is automatically speeded up and in this manner a practically steady "pull" is maintained. It would, of course, be just as easy to connect this gas governor to a suitably designed shunt regulator as to a steam throttle valve, and there is no reason why the electrification of the main exhausters should not be a complete success, always provided that the supply of electrical energy to the motor can be maintained as uninterruptedly as the steam supply to an engine can be.

The right time for the consideration of the question of driving the exhausters by means of electric motors is when the entire question of the electrification of the works power plant is under discussion, and it then

becomes a very simple matter to install a plant which will meet any demand, however exacting, that may be made upon it. When, however, the question of converting the exhausters to electric driving arises as a result of the success which has attended the electrification of other machines, it is often found that the general arrangement of plant that well served the purposes for which it was originally installed is utterly unsuitable for such exacting work as exhauster driving.

In the past, too much has been left to contracting firms and to local electricians, and the consultant's fee that has been saved turns out to be a bagatelle compared with the ultimate expense which has to be faced in order to render an ill-conceived installation capable of carrying important loads uninterruptedly.

Water-gas Exhausters.

It has been emphasized in the preceding paragraphs that absolute continuity of operation is the first essential in connection with the driving of coal-gas exhausters, but in the case of the exhausters used for the handling of the gas from the water-gas plant, such absolute continuity of running, while very desirable, is not so essential, owing to the fact that a relief holder is installed between the gas generators and the exhausters. A short stop on the part of the latter would simply mean that this holder would rise, and exhausting would have to be resumed at a slightly higher rate for a short time, in order to bring the holder back to that height at which it was found desirable to work it. It is usually the practice to work these exhausters at such a speed that the relief holder is maintained a few plates from the ground-level so that, in the event of an exhauster stopping, the holder is free to rise a considerable distance before it becomes necessary to shut down the gas generating plant.

Rotary Washers and Pumps.

In connection with the purification and by-product recovery plants a considerable use is made of large rotary horizontal low-speed and vertical high-speed washers, and as these units of plant are in continuous use they offer a very tempting load (from the load-factor point of view) for electrical operation, as do also certain of the larger pumps serving as auxiliaries to the main washers.

The application of electric motors to these machines presents very little difficulty, but in the case of the horizontal washers a considerable speed reduction has to be effected, the average speed of these washers varying from 2 to 5 revolutions per minute. In the absence of any existing reduction gear the electrification of such machines would involve a rather heavy outlay, quite apart from the motor and control gear, but in most cases the work can be very cheaply and efficiently carried out by regarding the existing steam engine as a reduction gear. The connecting and eccentric rods of the engine having been removed, a belt drive can be taken either from the motor direct, or via a single reduction gear, to the flywheel of the engine, and many modifications carried out in this manner have been found to give the greatest satisfaction.

The many small pumps used on a by-product recovery plant are a thorn in the side of the engineer in charge of a modernization programme, and the expenditure involved in scrapping them in favour of belt-driven ram pumps is comparatively slight compared with the economy which such a change must bring about. Where such pumps are in the vicinity of a washer or other large unit of electrically-driven plant it is often possible to drive them from some portion of the washer-driving gear, but in the absence of such accommodation the best course is to arrange the pumps in groups according to their duty and hours of running, and to drive each group by its own motor. Individual driving in connection with such small jobs is a mistake, and every effort should be made to keep the number of motors in chemical recovery plants as small as possible.

A class of pump which greatly facilitates the modernization of by-product recovery plants is the battery type; this comprises a number of plunger-driven pumps accommodated in the same frame and driven by a common crankshaft, and by means of a suitable cross-head and removable cotters any plunger can be picked up and dropped at will.

In the case of large pumps it is generally worth while making some attempt to convert them for electrical operation instead of replacing them with a modern type of pump expressly constructed for motor driving, as it frequently happens that the connections are of such a special nature as to render it a very difficult and costly task to install a new and probably quite different type of pump.

The electrification of pumps in connection with the average old type of by-product recovery plant is a particularly attractive proposition from the fuel-economy point of view, inasmuch as these pumps were generally laid down specially for the tanks and other apparatus in conjunction with which they had to work, and with an utter disregard to the long and generally exposed runs of steam pipe necessary to provide them with their power.

Gas Boosters.

For the purpose of augmenting the gas pressure in remote portions of the district of supply, or in order to ensure an adequate supply to a rapidly growing district which may have outgrown the capacity of its supply mains, centrifugal pressure-raising fans are frequently employed. In cases where the fan was required to give considerable differential pressure, steam turbines held the field for a considerable time owing to the very high speeds at which the small De Laval turbines were capable of working, but recent improvements in the design of centrifugal fans have brought this service within the scope of the electric motor.

Such installations usually comprise a variable-speed motor direct-coupled, on a common base plate, to a centrifugal fan. A flexible coupling is much to be preferred to the ordinary cast-iron coupling which is generally supplied by contracting firms. These pressure-raising fans are of considerable value for rapidly transferring the gas from one holder to another in cases of emergency or necessity.

In common with coal-gas exhausters it is essential that the supply of electrical energy should be reasonably immune from the possibility of even momentary interruption before the electric motor can be entrusted with this service.

Starter regulators are necessary in connection with the above boosters in order to start at a very low speed so as to avoid causing a pressure wave on the district.

Blast Fans.

The blast fans for maintaining the generator heats in a carburetted water-gas plant offer a particularly attractive field for the attention of the engineer who is engaged in stopping waste and who is incidentally in search of a good load factor. The power required to drive these fans varies from 20 to 70 b.h.p. according to the capacity of the sets. The load is usually a 24-hour one. These fans are nearly always belt-coupled to their steam engines, and the cheapest method is to replace the engine with an electric motor running at a moderate speed and to retain the belt drive. This permits of the job being done without the necessity of altering the position of the fan itself or of interfering with the blast main, as would be the case if a direct-coupled set were installed.

An interesting feature in such conversions lies in the necessity for the provision of some form of remote-control accelerating gear by means of which the fan may be speeded up or slowed down by any one of, say, three or four operators. This applies to a fan which serves three or four gas-making sets each of which would have its own speed-controlling device. These sets work in a series of cycles, say 4 minutes "blow" and then 5 minutes gas-making "run," then 4 minutes "blow" and so on. Each operator at such regular intervals either slows down the fan or relinquishes the control of it to another operator whose set may be blowing, the control of the fan passing from one operator to another according to the cycle which they are working.

Typical English Installation.

As illustrating the extent to which electric power is employed for the operation of the various units of plant within the precincts of a modern gas-works, the following particulars relating to the plant at the Coxside works of the Plymouth and Stonehouse Gas Light and Coke Company may prove of interest.

For the past 8 years the author has been engaged in the gradual modernization of the plant at these works, and although still much remains to be done he believes that more use of electrical power is made on these works than in any other gas undertaking of a similar size in the United Kingdom.

The original plant laid down in 1910 consisted of an electrically-driven stoking machine, and a coal store telpher together with three motors for the operation of coal and coke conveyors. The current required by this small plant was generated by a pair of "Peache–E.C.C." generating sets, each of about 40 kw. capacity. At that time a large number of single-cylinder non-condensing steam engines were used about the works, and created so large a demand for steam as to deprive the water-gas and by-product recovery plants of the steam so essential to their efficient operation, in spite of the fact that no less than eight 30 ft. × 8 ft. Lancashire boilers were in use.

As an alternative to the installation of additional boiler power involving the erection of a new boiler house and stack on an already congested site, and the employment of an additional 8-hour shift of men, it was decided to replace the steam engines by electric motors. During the past 8 years no less than 51 electric motors of a total of 577 h.p. have been installed, while the capacity of the power station has been increased from 80 kw. to 540 kw.

All the steam required for the generation of electrical power is now raised by a battery of three 30 ft. × 8 ft. Lancashire boilers, one of which is always down for cleaning.

Year ending 31st March	Electricity Generated, B.O.T. Units		Load Factor, per cent
	Total	Per 1,000 cub. ft. of Gas sent out	
1912	149,000	0·128	28
1913	170,000	0·138	28
1914	203,000	0·160	27
1915	224,000	0·166	28
1916	263,000	0·190	29
1917	315,000	0·224	32·8
1918	405,000	0·278	40
1919	498,000	0·350	47
1920	620,000	0·429	50

In place of the high-grade coke once used, these boilers are now fired with a low-grade breeze, and in spite of this the tonnage required over a given period is much less than formerly. In October, 1919, the annual output of the generating station was about 800,000 B.O.T. units, and when the conversions now in hand are completed it is estimated that between 1 and 1¼ million units will be generated annually.

Unfortunately, gas engineers are slow to avail themselves of the facilities which electrical driving affords for the accurate determination of the relationship between work done and current consumed, and it is consequently very difficult to obtain any reliable data in this respect. This being the case the author much regrets that the only data which he is able to include in this paper, so far as stoking machinery is concerned, is that referring to the machines under his care. Many engineers using electricity on their works have not the remotest idea of the amount of coke or coal they can handle by a given expenditure of electrical energy, and are too prone to look upon the integrating wattmeter and the recording ammeter as expensive luxuries.

One of the most valuable instruments for use in connection with telpher and stoking-machine installations is a recording wattmeter having a specially fast clock-work movement for the chart. By the use of such an instrument a valuable check can be kept upon the work of the different shifts, and any loss of time in the various

operations can be detected and rectified before it becomes a fixed habit. The use of these instruments enables an engineer to keep his finger on the pulses of the various units of plant, and to detect incipient faults, not only in the electrical equipment but also in the machines to which the motors are coupled.

The growth of this plant during the past few years may be gathered from the table on the previous page.

During the year ending 31st March, 1919, the 498,000 units generated were distributed as follows:—

	Units
Coal-handling plant	154,000
Coke-handling plant	95,000
Purification plant	120,000
Carburetted water-gas plant	87,500
Machine tools, lighting, etc.	41,500
Total	498,000
Average daily output ..	1,364

Generating Plant.

Although the purchase of electrical energy in bulk from an outside source offers a very convenient alternative to the installation of a private generating station, it is generally considered undesirable that so vital a public service as gas supply should be dependent for its continuity upon an extraneous source of power. In the majority of gas undertakings using electricity for their various units of plant, power is generated by a private plant within the precincts of the works. By far the greater number of such stations are equipped, naturally enough, with gas-driven sets, and no better proof of the suitability of the gas engine for such purposes is needed than the maintained economy and reliability with which these sets run, year in and year out, under conditions that are anything but ideal.

It is, however, a fact that in many cases the type of plant was chosen more with an eye to immediate convenience at the time of installation than to the ultimate uses to which it would be applied. In most cases the primary installation of such plant marks a period of transition in the history of a works, and it is usually put in at a time when the whole works is in the contractor's hands. With new gas-manufacturing plant being erected, and innumerable matters to be attended to, there is a very natural reluctance to undertake more work than is absolutely essential for the supply of current to the new sections of plant.

The alternative to a supply of power from an outside source lay in the installation of a gas-driven generating set of just sufficient capacity to meet the demand created by the new sections of plant. Had more attention been concentrated upon the wide range of purposes for which electrical power might have been advantageously employed, it would have become obvious that there was every justification for the increased capital outlay necessitated by the installation of good steam plant.

The fact that most works are more or less compulsorily burdened with a constant supply of low-grade steam-raising fuel has not been so well recognized as might have been expected, and in only a few cases has advantage been taken of the exceptional facilities afforded by breeze for the generation of cheap power.

On many gas-works breeze is practically a drug in the market and its accumulation frequently causes inconvenience and necessitates labour charges for stacking, yet from 5 to 6 lb. of water may easily be evaporated per pound of fuel burnt under proper conditions.

On a large works no electrification scheme, however extensive, can totally eliminate the demand for steam, and it follows that certain boilers have to be kept in commission. This fact, coupled with the presence of a supply of coke breeze, establishes a very strong case for the employment of modern steam plant for the generation of the electrical energy required, at a far cheaper rate than could be achieved with gas-engine driven sets. However carefully the coke may be handled most works produce sufficient breeze for their own requirements, and unless the cost of gas into holder happens to be very low, or a good price for breeze can be obtained in the district, the installation of steam units is the most economical proposition for a works which means to make serious use of its electrical plant.

Where the general condition of existing boilers is such as to warrant their continued employment in conjunction with steam-driven generating sets, a considerable saving in capital outlay may of course be effected, but it often happens that the interests of ultimate economy are sacrificed by the retention of low-pressure boilers for this purpose, as the economy of the plant is handicapped by high fuel costs which could have been avoided had new high-pressure boilers been installed for the generation of electrical energy.

Gas-driven Sets as a Stand-by.

As a stand-by to the steam units, a gas-driven set of sufficient capacity to serve the more important units of plant is a valuable investment and permits of the most comprehensive overhaul being carried out on the steam plant with a degree of convenience and economy which would be impossible in an "all steam" station. The elaborate and costly precautions so often adopted in public electricity-supply stations in order to guard against a failure of supply are no less essential in the private station on a gas-works which adopts electrical driving entirely, unless it so happens that one gas-driven generating set has been also installed.

The installation of such a unit permits of a much simpler and less costly lay-out of steam plant in both the boiler house and engine room without sacrificing the high factor of safety, besides making it possible to shut down the steam plant altogether should the necessity arise. A further advantage which the presence of such a set in the works power station confers, lies in the fact that it affords a standing testimony to the cleanliness and efficiency with which a large user of electrical energy may generate electrical power by means of gas-engine sets.

This argument is not advanced as a reason for a works to install such a unit of plant, but its value in this connection cannot be overlooked. With both input and output accurately metered a gas-driven

generating set in the works station is a powerful selling weapon in the hands of a gas salesman, particularly in a large industrial district where the area covered by the gas mains happens to be greater than that served by a public electricity supply authority.

Waste-heat Installations.

Up to the present very little attention has been given to the subject of waste-heat recovery, and gas engineers would do well to follow the lead of the metallurgical industries in this respect. The practice of raising steam by the employment of flue-gas-fired boilers (preferably of the tubular type) is by no means a new idea, but, so far as gas-works are concerned such installations are rarely met with, in spite of the fact that such works are usually well to the front in the recovery of all by-products of any value.

The lethargy and conservatism to which the author has already alluded are, no doubt, to a certain extent responsible for the lack of enterprise in this direction, but another and more tangible explanation lies in the reluctance of the gas engineer to take any step which might have the effect of impairing that chimney draught which is so essential to successful carbonization.

Faith in old and well-established institutions dies hard, and gas engineers, like many of their brethren in other branches of the engineering profession, are slow to acknowledge the advantages of artificially-induced draught in connection with their retort-house furnaces. Having regard to the fact that the maintenance of even heats is so important a factor in satisfactory retort-house working, it seems strange that induced-draught fans are so rarely employed, even for no other reason than that their use ensures independence of atmospheric conditions, and quite apart from any waste-heat utilization scheme, in connection with which their employment is of course essential.

In ordinary gas-works practice the volume of high-temperature waste gases is, of course, very small compared with coke-oven and blast-furnace plants, but this is no reason why the most should not be made of them. The quantity available is at least sufficient to warrant a reasonable expenditure with the object of harnessing them and obtaining useful work from what would otherwise be a waste product, and no difficulty should be found in getting an evaporation of 2 to 3 lb. of water for every pound of coke burnt in the retort furnaces. This estimate is based upon the coke used having a calorific value of about 12,000 therms * per pound, and an average flue-gas temperature of about 500° C. In one case known to the author the waste heat from about 16 retort settings is passed through a waste-heat boiler installed in the main flue. The average hourly consumption of coke in the furnaces is from 11 to 12 cwts., the feed water temperature is from 90° to 100° F., and an evaporation of about 3,000 lb. per hour is obtained. This particular plant, it may be observed, is by no means a model installation.

In another proposal with which the author is dealing, a guaranteed minimum evaporation of 6,000 lb. per hour is quoted in connection with a group of settings consuming about one ton of good gas coke per hour. This installation includes the use of a draught-inducing fan, so that the net advantage which this plant would confer on its user would be this guaranteed minimum evaporation, minus the power taken by the fan, probably about 700 to 800 lb. of steam per hour.

In round figures there should be no difficulty in any works equipped with good modern steam-driven generating sets obtaining all the power required for the operation of their various units of gas-making plant from a waste-heat boiler fired with flue gases from the retort-house furnaces. The output from such a boiler would of course only vary according to the number of settings in use and would be absolutely constant so far as daily working was concerned. With variations in the load, blowing-off would naturally take place unless a battery installation were provided to take a charging current at periods of otherwise light load, or unless great pains had been taken to secure a good load factor.

Where capital expenditure had already been incurred in respect to an installation of high- or moderate-pressure reciprocating sets, the waste-heat boiler would be designed to give steam at such a pressure as would enable it to work in conjunction with the existing steam plant.

Where, however, a fresh start is being made in regard to power plant, there is, in the case of a fair-sized works favourably situated in regard to a supply of water for condensing purposes, a strong argument for the employment of a waste-heat boiler working in conjunction with low-pressure turbine units, the necessary stand-by taking the form of a gas-driven generating set.

The "Thomas" Meter.

One of the most recent applications of electricity on a gas-works, and one which will inevitably conduce to a much more efficient degree of scientific control, is the use of the "Thomas" electrically-operated meter for the measurement of gas in large volumes. The use of this meter places the gas engineer in the same position in regard to his output as the central station engineer, inasmuch as it provides him with the same facilities for recording his hourly output, variations in output, and peak loads, in the same manner as in electricity undertakings, substantially the same instruments being used in the two cases for the control of the output.

The principle upon which this meter works was established by Professor C. C. Thomas at the University at Wisconsin in the course of experiments bearing upon the heating of flowing gases through known temperature ranges. These experiments proved that a given quantity of industrial gas requires a practically constant amount of heat to raise its temperature through a fixed range.

Fig. 6 will enable the principle of this meter to be easily grasped. In the vertical plane a short length of gas main is shown, the direction of flow of the gas through which is indicated by arrows. In this main, one heating element (F), and two temperature-resistance elements (A and C) are placed, these elements consisting of special circular grids and the element F being placed midway between them. Suitably insulated

* British thermal units.

connecting wires are brought through the wall of the main for connection to an outside source of current supply. The main in which these elements are installed consists of a special casting for introduction between existing flanges.

In the figure, A and C, together with two external resistances (B and D), form the four elements of a Wheatstone bridge into which a galvanometer (E) is connected in the usual manner. At the same given temperature, the resistance of the four limbs A, B, C and D are equal, and the bridge is in a state of balance. Upon a current of electricity being passed through the heater coil (F) it follows that heat will be imparted to the flow of gas, and through that medium will be carried to the temperature coil (A), the resistance of which will hence be increased. Hence, the bridge will be thrown out of balance by an amount corresponding to the swing of the galvanometer needle.

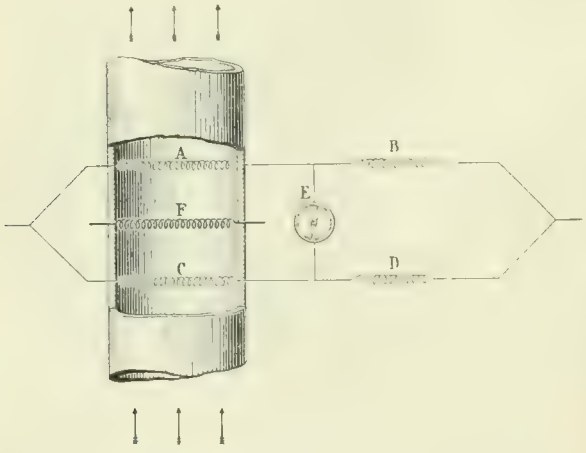

FIG. 6.—Diagram showing principle of the " Thomas " meter.

The galvanometer (E) is of special construction, and is enabled to act as a current regulator in respect to the heater coil by means of a special mechanical arrangement which periodically clamps this needle between selector contacts. These contacts control the current through the heating coil via small electrically-operated pawls, which in turn actuate a main rheostat. In practice it is customary to supply enough current to the heating coil (F) to bring about a difference of 2 degrees F. in the gas between the points at which the temperature-resistance elements (A and C) are installed.

The amount of current necessary to bring about this constant difference in temperature varies with the volume of gas passing at any given moment, and this energy is measured on both a watt-hour meter and a recording wattmeter calibrated in cubic feet of gas instead of the usual electrical units. The indications thus obtained register the flow of gas in cubic feet without any corrections whatever being necessary for either pressure or temperature variations.

It will be clearly understood that this apparatus naturally divides itself into two general parts: (*a*) The special element housing in the main pipe line. (*b*) The recording panel on which is mounted the heater current control devices and a small continuously-running motor-generator for the supply of power to the heating and Wheatstone bridge elements. This panel may be mounted in a convenient place at any reasonable distance from the actual housing in the main pipe line.

It would be superfluous to emphasize the benefits which the possession of a continuous graphic record of the total output on any particular main confers upon the gas engineer. It is an advantage which central station engineers have always enjoyed but which has only recently been afforded the gas engineer by the employment of this meter. The standard station meter hitherto used on gas undertakings is of such dimensions as to necessitate the erection of a fair-sized house to accommodate it, and apart from all the other advantages of the " Thomas " meter a great saving in ground space and building costs is effected by its installation.

CONCLUSION.

The author has endeavoured to indicate the increasing extent to which electrical power is being used on modern gas undertakings, and this fact, together with the growing popularity of the internal-combustion engine for the purposes of electrical generation, particularly as regards large capacity units working in conjunction with modern by-product recovery plants, must ultimately result in members of both the gas and electrical professions taking a broader and altogether more reasonable view of the entire subject of power competition.

A further result of modern practice in the above connection lies in its effect upon the training and experience of the modern gas engineer, which must result in future in widening the scope of the industry. From small beginnings large issues spring, and it is impossible to estimate what important results may arise from the small introductory use, a few years ago, of electric power for the operation of a single unit of gas-works plant.

It may even lead in certain districts to the gas-works being the sole place at which coal will be used on a large scale, and therefore the source from which electricity purveyors will draw the necessary fuel for the operation of their generating sets. Alternatively, it may lead to an extensive fusion of gas and electrical interests in connection with big-scale joint undertakings, " joint " not only as regards business control, but in the technical sense of the word for the supply of light, heat, and power to the public.

THE EFFICIENCY OF HIGH-TENSION TRANSFORMERS AS USED FOR X-RAY PURPOSES.*

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For several years past it has been evident to many radiologists that, in the absence of some fundamental change in our methods of generating X-rays, further development in the science of radiology would be limited to matters of detail. Great improvements in apparatus and in methods have been brought about, especially during the war, but so far as the real essentials are concerned we are no further on than we were a dozen or more years ago when, perhaps without realizing it, we arrived at a sort of blind end out of which we have been trying to find a way.

The various steps that have marked the development of radiography are familiar to most of us. The demand for shorter exposures led to the production of more powerful coils and tubes capable of receiving these heavy currents—at one time the race between the coil maker and the maker of X-ray tubes was not without some elements of excitement. Almost it seemed that, given a sufficiently large coil and suitable tube, instantaneous radiography would follow as a matter of course; but we were not long in finding out that the induction coil was subject to limitations of an inherent nature—the self-induction and impedance of the secondary winding—that most effectually barred any real progress beyond a certain more or less well-defined limit. The monster coil was a disappointment that increased with its size, and it is doubtful if we have anything that can compare with a good 12-in. coil and mercury break, so far as it goes, as an efficient means of exciting an X-ray tube. The use of the electrolytic interrupter satisfied the demand for more current through the tube, but the large amount of inverse current was a serious drawback, which even the valve tube (itself a very unsatisfactory instrument) failed to remove entirely. Still the cry of the radiographer was for more milliamperes, free from inverse current, feeling quite sure that once obtained all would be well. At this juncture an electrical engineer—my friend Mr. (now Dr.) H. Clyde Snook—brought forward his high-tension transformer, with a closed magnetic circuit and mechanical rectifier, giving a perfectly unidirectional current in larger volume than anything of which we knew. The promised land seemed well in the foreground and we hailed him as our deliverer. We have had this instrument now for close on a dozen years, and there is no doubt that it has been of enormous service to the whole science of radiography, but can anyone of us who has had a large experience in its use say that it has realized our full expectations? Do we get a shortening of the exposure in proportion to the greater current as compared with that from a coil? Or again, given the same screen effect, can we get the same result on a plate for a given exposure as in the case of a coil? With all the good points of these machines, the fact remains that to these questions only a negative answer can be given; and machines of the Snook type are very inefficient as producers of useful X-rays. In the early days of our disappointment we hid our chagrin by blaming the X-ray tube, and possibly many radiologists continue to do so. During the years of the war it is true we had much to put up with, but not entirely due to faults in the X-ray tube as such, or on the part of those who made them for us in the face of great difficulties. My own belief is that the best quality of X-ray tube such as we had at the outbreak of war is a wonderfully efficient and satisfactory implement, more sinned against than sinning, but quite unable to show its possibilities under existing conditions of use.

The chief object of this Joint Meeting is to explain our difficulty to the members of the Institution of Electrical Engineers and the Röntgen Society in the hope that they may be able to suggest a more efficient means of exciting our X-ray tubes. As some of them are not practical radiologists I think it would be as well to explain one or two fundamental matters, so that they may the better appreciate our requirements. The essential need of the radiographer is a supply of X-rays having a high degree of actinism and with sufficient penetration to pass through the thickest parts of the body without serious loss of this actinism. A "soft" or low-resistance tube gives off very actinic rays which have only a low power of penetration; we can increase this penetration by raising the voltage of the current applied to the tube, but only to a limited extent under present conditions, as I shall explain presently. We can have more highly penetrating rays by using a "hard" or higher resistance tube, but this is accompanied by an equal, or even more rapid, falling off in the essential property of actinism, and plates made with hard tubes are of inferior quality and little diagnostic value except in the case of fractures and other of the simpler applications of radiography. How then are the prime requirements of the radiographer to be met?

Before attempting to answer this question we should first critically examine existing methods of operating X-ray tubes, and the only two we need consider are the induction coil and the high-tension rectifying machine of the Snook type. The large static machine is out of

* Throughout the body of this paper, as distinct from the title, the word "transformer" refers to apparatus having a closed magnetic circuit as distinguished from the "coil" with its open straight core.

the question, in this climate at least, and the high-tension transformer with valve tubes to suppress the waves in one direction met an early death without many tears being shed.

With the aid of an oscilloscope and a rotating mirror some very interesting phenomena are presented for our study. If both terminals be connected in turn to the coil and transformer and a weak current be passed, we get more or less characteristic current curves of each, and the amount of current being very small the curves are not distorted by self-induction or impedance to any appreciable degree. Only the negative pole glows, and its digression from the zero line is in direct proportion to the impressed voltage. In the mirror the coil shows us a curve having the general characteristics of Fig. 1, while that of the transformer is shown in Fig. 2, a rectified double-sine curve. In the one we have an alternating current quite unsymmetrical in both form and duration; in the other a series of perfectly regular sine curves, identical in form, duration and sequence. The periodicity remaining constant the curves are narrower and more numerous the more slowly the mirror is rotated; rapid rotation widens them out without affecting the height, all this being due to retinal persistence.

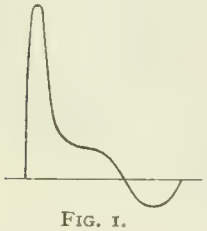

FIG. 1.

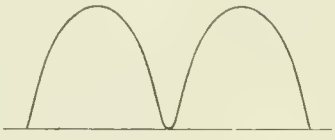

FIG. 2.

Here we have two voltage curves with widely different characteristics, and practical experience has taught us that the first is the more efficient for our purpose, up to the limit of its capacity. We get more penetration and more actinism for a given current, greater steadiness, less heating, and a longer useful life for the X-ray tube. A further point in favour of the coil current is that it will keep a tube working smoothly on a lower reading of the milliammeter. Every tube has a certain amount of inertia and requires a higher voltage to start it than to maintain it in action; the sudden rise at the moment of "break" readily overcomes this inertia.

The explanation of this superiority of the coil over that of the transformer is a problem that has puzzled many radiologists—few more than myself. The mean value of the current through the tube is of no help to us in estimating efficiency, and we must have more detailed information as to what actually takes place.

I think it is generally agreed that penetration is dependent on electron velocity within the tube, which in turn is dependent on the impressed voltage. Thus it would appear that the impression of a sustained high voltage on a tube in the best condition to ensure the greatest actinism should meet our every requirement. By "sustained" I do not mean "continuous" in the ordinary acceptance of the term. For reasons which will appear in the course of this paper my view of the ideal current is one consisting of extremely high-voltage impulses, of very brief duration as judged by ordinary standards, yet sufficiently sustained to have an appreciable time factor. Such current as would pass through the tube by virtue of those lower voltages represented in the lower part of the above curves should be suppressed or diverted. If the voltage of the initial impulse be sufficiently high and sustained for even a small fraction of a second, one will be enough for any ordinary purpose in radiography.

This is the problem to be solved, and, as others may be disposed to disagree with me, I will now briefly relate those observations and experiments that have led me to these conclusions.

In the days of comparatively feeble apparatus we were troubled with the inverse wave of the coil current as soon as we began to use as our source of supply the public supply mains with their higher voltage. To suppress this undesirable element the simple "point and plate" spark-gap in series with the tube gave excellent results so long as the current was insufficient to establish an arc. This simple device gave us some very valuable indications that were for the most part ignored, and at the best did not receive the attention they deserved. Its action was of course that of a resistance gradually increased until all evidence of inverse current disappeared from the tube. Incidentally it also suppressed a corresponding amount of the current in the proper direction; the two being equal and opposite, the milliammeter reading was unaffected. Notwithstanding this elimination of a portion of its proper current the X-ray output of the tube was also unaffected—at times I thought it was actually improved, but as I could not reconcile this with prevailing ideas I hesitated to commit myself to any definite statement. For all that, I carried my observations a step further and, instead of leaving the spark-gap just sufficiently wide to eliminate the inverse current, I opened it still further until the milliammeter reading began to fall to a quite definite amount. Still the X-ray output remained appreciably unaffected as judged by plate and pastille. Opening it still further, the X-ray output began to fall off, but not to the same extent as would be expected from the diminution of current. Here again, I thought I detected a distinct gain in efficiency, but ascribed it to some vagary of the tube itself—and they had many in those days. At this stage the spark-gap ceases to be a satisfactory instrument—unpleasantly noisy in the open, and troublesome from the rapid formation of nitric fumes if enclosed. The obvious lesson from these observations is that it is through the influence of the higher voltages alone that we get useful X-rays from our tubes. Below a certain point the resultant rays have little or no penetration and for our purposes are worse than useless.

This being the case, the question naturally arises as to why the coil is unable to meet our requirements, considering the enormous voltage available at the moment of "break." If we examine an oscilloscope in series with an X-ray tube strongly energized by a coil, with the mirror rotating at moderate speed the explanation is at once available. If we consider the enormous potential set up by the coil when arranged

for a rapid exposure—capable of bridging 12 inches or more of air—and the relatively low resistance of an X-ray tube in the best condition for radiography, the initial rush of current must have a very high magnitude. The oscilloscope proves this to be the case, but it also shows that its duration is extremely short, so short indeed that rapid rotation of the mirror has little if any effect in opening it out laterally, and also it is extremely difficult to be sure of its upper limit where it tails off to nothing so gradually that we cannot be sure where the end is. This is partly due to the self-induction of the secondary, cutting off this rush of current almost simultaneously with its birth. It is also due in no small degree to something inherent in the X-ray tube itself. Notwithstanding its brief duration —its correct representation in a diagram would be as near Euclid's definition of a line as anything I know of in nature—it is this impulse that makes the coil current so efficient up to the limit of its capacity. It is the absence of any such high-voltage impulse that keeps the efficiency of the transformer current so low. For the same current through the same tube the top of the transformer curve extends little more than half-way to the highest point of that of the coil.

Of the total radiation from a tube energized by a coil, probably no more than 20 per cent consists of useful rays; energized by a transformer the proportion is probably less than 10 per cent. This is of course a deplorable state of affairs, which is not made any more palatable by the knowledge that the efficiency of both coils and transformers is lower than it need be, for which radiologists have only themselves to thank. I am fully conscious of the seriousness of this charge, but so long as the radiologist takes milliamperes as his sole criterion, quite regardless of how they are made up, just so long will the further improvement of existing apparatus be delayed. There is no inducement for the manufacturer to improve efficiency—he must gather up and use every available fragment of current if he wishes to sell his apparatus—because radiologists as a whole have learnt nothing from the disappointing efficiency of the high-tension transformer. Yet improvement in efficiency is not only possible but easy, and manufacturers will readily do this for us if only we make reasonable demands backed up by knowledge of what we really do want. As an instance of the present state of things, take the case of a certain mercury break to which is attached a mechanical rectifying device that has achieved some success, and of which some members may have had experience. It arose out of a desire to apply the principle of the Snook machine to the coil, and of course my first impulse was to rectify the inverse wave and pass it through the tube. Fortunately, before I got very far with this idea I recalled the lessons learned from the spark-gap and decided to eliminate it altogether; but still somewhat obsessed as I was at that time with a desire for more milliamperes, I arranged the rotating wires to pass fairly close to the collectors, giving the latter the form of a sector. Even then I was criticized for not providing tinsel brushes on the ends of the rotating wires to ensure good contact. In vain did I plead that I was already picking up current of little or no value, but the Electro-therapeutics Section would have none of it. Feeling sure of my ground, and still following the lesson of the spark-gap, I shortened the sector to a point and finally altered it to a ball. Then I began to increase the clearance between the ends of the wires and the balls, and every alteration was followed by a gain in efficiency, steadier action, less heating, and longer life of the X-ray tube. I am not prepared to say just how far we might go in this direction, but it gradually becomes noisy and insulation difficulties begin to arise. At present I know I am sacrificing a certain amount of efficiency for the sake of silence, but on the whole I am well content with my coil set.

When first brought out, this device was the subject of a certain amount of unfavourable criticism by certain manufacturers, who later on did not hesitate to copy it, and with an unwonted unanimity not one has remembered to acknowledge where they first got the idea. However, I readily forgave them when I saw how they had carried it out. Here again we see the baneful influence of the unreasoning and unqualified demand for milliamperes. In a recent number of the *Archives* there is an advertisement in which "actual contact on the high-tension collectors" is put forward as a special feature, whereas the fact is that this firm has gone to no little trouble and expense to lower the efficiency of the outfit with which it may be worked. This is, however, not so bad as the case of another firm who, in the effort to "go one better," rectify the inverse wave and pass it through the tube. So far from being an improvement it is no more than a complicated and costly means of spoiling an otherwise good machine.

This is not the way to improve efficiency; instead of demanding more milliamperes, let us measure the efficiency of our apparatus by the radiological result obtained from a given number of milliampere-seconds on both plate and pastille. That is the only thing that matters to the practical radiologist, and to increase this efficiency the manufacturer will be obliged to cut out the lower half of the coil curve and probably not less than 80 per cent of the transformer curve. That this radical departure from usual practice will be followed by a distinct gain in efficiency is not a mere expression of opinion; I have tried it and proved it to be true beyond all question of doubt.

With regard to machines of the Snook type, I had one of these installed at the West London Hospital some years ago and when delivered it was like most others—disappointing. It had the original cross-arms of wood in the rectifying portion. After a few months' use I began to shorten the collecting blades and after each alteration there was a gain in efficiency. For a given adjustment of the primary circuit the reading of the milliammeter steadily declined with each shortening of the blades until the latter were represented by only a point. The efficiency at this stage was at least equivalent to that of a coil. It should be mentioned that though the collector was but a point the current began to pass before the rotating conductor reached it, and continued to flow for a corresponding time after it had passed, so that a not inconsiderable portion of the top of the curve was made use of. I could not carry on with this as it brought insulation difficulties not

provided for in the design, and I had to be content with a sector about one-quarter of the original length. Even then the efficiency of the machine was practically doubled, the consumption of X-ray tubes was reduced in a most satisfactory manner, and they gave better service while they lasted. Latterly, after several years of hard work and unfavourable conditions arising out of the war, it had to be reconstructed, as to its moving parts at least, and I am sorry to confess I allowed myself to be persuaded into having a disc rectifier instead of the original wooden cross-arms. The efficiency is now back to what it was, or nearly so. The disc may be sound for mechanical reasons; radiologically it is bad, as at present constructed. Personally I prefer the original arrangement.

It may be somewhat of a surprise to some that practically all the views I have expressed up to this point, and all the experiments I have tried in order to improve the efficiency of X-ray apparatus, have sprung from observations with the oscilloscope and rotating mirror made as far back as 1904. I believe I was the first private individual in this country to acquire an oscilloscope, and shortly afterwards I gave a demonstration at a meeting of our parent society, The British Electrotherapeutic Society. It was my good fortune to have the co-operation of the late Dr. Lewis Jones, and well do I remember the first evening we spent with this fascinating instrument. We were frankly mystified, yet both felt that what we had observed was of great importance, though at that time we could not appreciate its full meaning. It was often referred to in our conversations during the all too few years he had to live. On that occasion we made a note to the effect that "the important and probably only essential part of the impulse through an X-ray tube is of extremely brief duration." Probably few men made more numerous intelligent anticipations than Dr. Lewis Jones and, fortunately, he lived to see the realization of many. Though we made the above observation together at the same time and place, I want him to have full credit for it; I believe that our methods of exciting X-ray tubes will be profoundly altered in the immediate future on lines that are the direct outcome of this observation. I prefer to picture to myself the intense pleasure it would have given him to have seen this through to its consummation, in addition to the privilege I now have of paying a tribute to the memory of one of the most excellent of men.

It will be remembered that these were the days of small coils and small tubes; the mammoth coils and the Snook machine were yet to come. When these and a host of other new things did come, together with new methods and new applications to be worked at, my oscilloscope was forgotten. It was not until I was approached on the subject of this meeting that I dug it out again and resumed investigations that should have been done years ago. It was not without some trepidation that I set it up for the first time to examine it in series with an X-ray tube and Snook transformer. In view of the wide difference in the voltage curves of this and the coil, and that the high-voltage impulse of the latter at the moment of "break" might quite well have been the determining factor in what we had observed, I had a great fear that what I was about to see might at least be difficult to reconcile with ideas firmly held for many years, if not refuting them altogether. There was no need for anxiety as it happened, and Figs. 3 and 4 show the general character of the curves, if such they may be called.

The width of the initial impulse (*a*) is the image of the electrode and does not indicate the proportion it bears in time to the whole. Rapid rotation of the mirror does not appreciably increase its width, while the rest (*b*) of the cycle, consisting of useless low-voltage current, widens out in proportion to the speed. I think we now have a complete explanation of the relative inefficiency of the transformer as compared with the coil. The initial impulse (*a*) does not reach so high as in the case of the coil for the same mean current through the tube, nor is it any more sustained. The high reading of the milliammeter is due almost entirely to part (*b*), which also overheats our tubes and generally behaves as a nuisance. The explanation of this unique phenomenon of the passage of a high-voltage current through an X-ray tube I must leave to the physicist, who I am sure will find it an interesting if not a difficult problem.

It is now easy to understand how efficiency was improved, (1) by the use of a spark-gap, (2) by increasing

FIG. 3.

FIG. 4.

the resistance in the secondary circuit of my mechanical rectifier, and (3) by shortening the collecting blades in the Snook machine; all three being no more than the provision of one or more air-gaps in the secondary circuit.

It should be remembered that with the relatively feeble apparatus in general use at the time these original observations were made with the oscilloscope, we were obliged to use tubes in a comparatively "hard" condition to get the necessary penetration. The gradual improvement in the construction of coils and transformers since then has enabled us to use tubes of considerably lower resistance, with a steady improvement in results. These "soft" tubes have a lower initial inertia as well and, as might be expected, the oscilloscopic appearances are not the same. The wave does not rise so abruptly; it shows unmistakable tendency to prolongation, and its fall is less rapid. Figs. 3 and 4 were obtained with a tube rather harder than is usual under the best conditions, but in the case of this transformer the main supply is a low-voltage alternating one, the least suitable of all for X-ray purposes. These altered appearances under modern conditions of working in no way conflict with my general principles; the oscilloscope merely confirms what we already know, viz. that we are "getting on."

It being my firm opinion that the initial impulse is the only part of the cycle that matters for our purposes, this is where we should concentrate our attention with a view to increasing its height—quite feasible as the success already attained with the "single flash" coil

proves—or by prolonging its duration, which may be more difficult. So far we have only partly succeeded in giving it an appreciable time factor. If we could do this, even to the extent of a very small fraction of a second, the problem would be solved so far as the requirements of medical diagnosis are concerned. Exposures would be similar to those common to daylight-photography under the most favourable conditions, and the flow of current through the tube would be such as to be more conveniently expressed in amperes, or at least in decimals thereof. Special provision will have to be made for screen examination, but radiography will be "instantaneous."

Having come to these views as a result of experience, experiment, and observation, it will readily be understood why I am disposed to regard what is known as the "single flash" monster coil with at least a friendly eye. Nothing else is possible if one is to be consistent. I have had no personal practical experience, for unfortunately there are very few examples in this country, but long before I had an opportunity of seeing one that is in regular use and the most excellent results obtained, I had committed myself to the opinion that the system was not only sound but in all probability would ultimately prevail. Having seen and examined the working of the installation at King's College Hospital, through the kindness of Dr. Robert Knox, and the extraordinarily fine results regularly obtained there, the matter is, so far as I am concerned at least, no longer one of conjecture. The apparatus is a revelation of simplicity, silence, and high efficiency. Exposures are the same for all parts, only the intensity of the discharge being altered by the primary resistance to meet the varying thickness of the different parts of the body. The best results are obtained with tubes of very low resistance, giving most beautiful contrast, a wealth of detail, and absolute sharpness of outline, even in the case of the heart, or in the event of movement on the part of the patient—voluntary or otherwise. As regards the effect of these intense discharges on the life of the X-ray tube, this is much less prejudicial than time exposures; we had already learned this from experience with the multi-anode electrolytic interrupter. I must leave further details of this system to those who have had practical experience with it. It is my firm conviction that the future of radiography is bound up more or less inseparably with the "single flash" system, and manufacturers would do well to give this matter their very serious consideration.

In the course of these comments by way of opening this discussion on behalf of the radiologist I have not attempted to cover the whole ground, and there are aspects of the question that must be left to others more competent to deal with them. I have indicated means by which existing apparatus may be improved in efficiency, and also the problems to be faced in designing better methods of exciting the X-ray tube. In advocating what is, in effect, a return to the coil—suitably modified—in preference to the transformer for radiography, I do not mean to decry the latter. I have both admiration and respect for a machine that has served radiology so well, and also for its inventor. In conjunction with the Coolidge tube there is likely to be an increasing demand for it in radio-therapeutics, but I think it should be so modified as to eliminate at least the lower half or even two-thirds of the wave. This alone will raise its efficiency to the level of that of the coil as ordinarily used, as I have already proved, while its greater output will give it corresponding advantages. But if the "single flash" coil will do all we want in radiography—and there seems to be no doubt on this point—I can see no advantage for the transformer. It is no small matter to get away from large and rapidly rotating parts with their inherent liability to break down, and the constant noise and vibration inseparable from such machines that are so undesirable in the examination room of hospital as well as private practice, however much they may be minimized by careful construction. And, after all, it is not impossible that the final and ideal apparatus may be quite different from anything we have at present, in which perhaps resonance or harmonics play an important part; but this is where I must give place to others conversant with these intricate phenomena.

I have been asked whether Figs. 3 and 4 are not figments of the imagination. They are nothing of the kind. They represent the appearance which we get if we take a fairly hard tube and connect it to a high-tension transformer. It is due entirely to the fact that the resistance of the tube was high. The entry of the current into the tube is delayed, and when it does enter, it enters suddenly and we get a high impulse at first, as we have seen. Remember that the width of that impulse is the image of the electrode—it bears no proportion, in time, to the rest of the phase—and as the mirror is spun faster and faster that image remains practically unaltered.

In presenting his paper, Dr. Morton said: I cannot do better, perhaps, than state what may be described as the text of my discourse.

Efficient radiation from an X-ray tube depends directly upon electron velocity. Such electron velocity as results from the flow of an undulating current through an X-ray tube is too low to produce efficient radiation. The radiation efficiency of any current applied to an X-ray tube will be increased directly as the character of its inflow partakes of the element of shock.

Since sending in the MS. of my paper I have been making some graphic records of what actually takes place with each electrical impulse through the X-ray tube in terms of resultant radiation. For this purpose I made a shallow trough of wood, covering the top with sheet lead, but leaving a slit approximately 0·75 mm. wide across the middle. A small frame that would readily pass along the trough under the lead cover was provided with a catch and spring release, the motive power being an elastic thread. The frame acted as a film carrier, the strip of photographic film being enclosed in black paper. In use the X-ray tube is centred over the slit, the frame loaded with a film and the elastic in tension. All being ready the tube is turned on for a second or two while the frame is released, carrying the film past the slit at a speed of about 20 ft. per second, which gives a convenient spacing under ordinary circumstances. For testing efficiency in apparatus,

X-ray tubes, or photographic plates and films, this simple expedient is most satisfactory and gives results that are comparable with a minimum of error. I made it a rule to develop all the films exposed during a test in the same tank and at the same time. Strips about 1 in. wide are convenient to handle and leave room to cut away parts that may have been damaged during manipulation. In the lantern slides now shown, narrow strips of these films are bound up between two cover glasses. These investigations have taught me a great deal, and were I writing my paper again it would be altered in some details of a minor character, but on the whole they tend to bear out my ideas very satisfactorily.

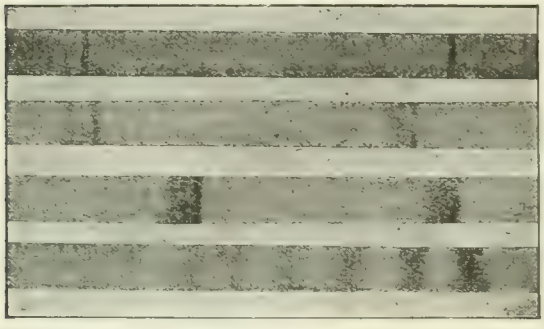

Fig. 5.

The top film (Fig. 5) was made under conditions as nearly as possible the same as when Dr. Lewis Jones and myself first used the oscilloscope: 10-in. coil, motor mercury break, 24 volts, and a Chabaud tube passing about 0·75 milliampere. With a trifling allowance for diffusion the slit and its image on the film are exactly the same width, and the image is not appreciably wider with the film travelling at about double the speed —exactly in keeping with our original oscilloscopic appearances. As the power of the apparatus increases, a

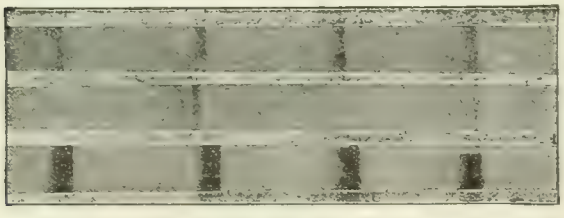

Fig. 6.

second image of the slit appears immediately after the first one, but much fainter. It remains practically the same with a higher film speed though the width of the space increases, showing that there is a definite time factor here at least. The second strip is from my own coil showing four images, more easily seen in the third where an intensifying screen was used. The film speed was lower in this instance and the images closer together. The fourth strip is the result of one interruption from the "single flash" coil at King's College Hospital which I obtained through the kindness of Dr. Knox. The film speed was about 30 ft. per second. It will be noticed that the impulses are appreciably sustained and as a rule 10 can be made out, gradually diminishing to zero. So far as my observations go, the use of an intensifying screen does not increase the number of these images—it merely enhances the visibility of those seen without its use—and the same

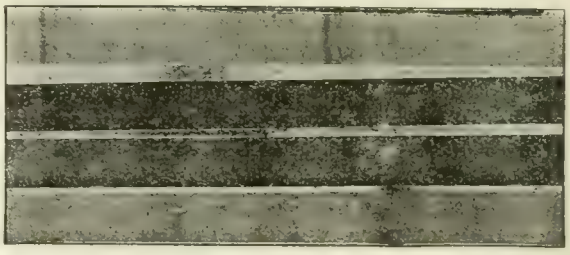

Fig. 7.

applies to chemical intensification after development and fixing.

Fig. 6 shows the influence of film-speed—that of the middle strip being almost exactly double that of the other two. The lowest one shows the effect of the intensifying screen, and between the low speed and the fluorescence of the screen the images have run into one another

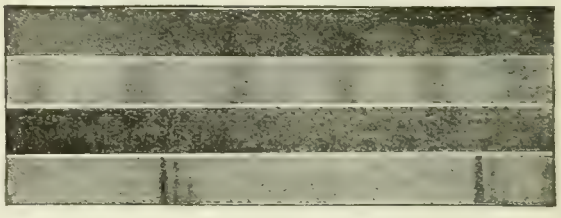

Fig. 8.

almost to the extent of continuity. The images of the slit do not widen with the increase of speed.

As we increase the distance between the anticathode and the film the images naturally get fainter, the weaker ones disappearing rapidly. The upper pair were from a coil, the lower from a transformer (Fig. 7).

Fig. 9.

In all, the current was 12 milliamperes. The anticathode film distance was 5 in. for the first and third, and 16 in. for the second and fourth. I happened on a poor film for these, but I show them because all the conditions were the same and are therefore comparable. A soft tube was used—the resistance equivalent to $2\frac{1}{2}$ in. of air—for these, and the same tube for the films shown in the next slide.

The first three strips are from a tube excited by a transformer at a distance of 15 in. from the film, the current being 20, 30, and 40 milliamperes respectively; the last is a coil record (12 milliamperes) for comparison (Fig. 8). The shading bears a direct relation to the wave-form and shows that only the peak is of any value for our purpose. Increase of current through the tube does not produce anything like a proportionate blackening of the film, from which it appears that the useless current bears a rapidly increasing proportion as the total current through the tube is increased. I have known for long that we do not get proportionate shortening of exposures with greater current from the transformer as we do from the coil. These films are at least a help in understanding this matter.

The last slide (Fig. 9) has interested me very much. The tube was excited by a 16-in. coil worked through a synchronous break from the alternating main—220 volts, 50 periods. I remember, when examining this coil with the oscilloscope a few days before, the unusual image it gave in the rotating mirror. It is a difficult thing to describe, but was easily seen by those present. About one-third of the way from the commencement there was a fairly deep notch with convex sides, continually varying in width, even disappearing at times, with the fluctuations of the speed of the mirror. I was puzzled but had to leave the matter for future investigation. When I came to examine these films I saw what I think is the explanation. As I understand, these coils have two primary windings, reversed to each other and each with its own pair of contact blades in the interrupter. The connections are such that all the impulses through the primary are in the same direction. Alternate impulses through the tube are generated by one primary winding, the intervening impulses by the other, and this film shows that the two sets are far from being equal. What I saw in the oscilloscope was the result of superimposing two dissimilar sets of waves which would give an altered appearance with every degree of departure from accurate registration. I venture to say I have found out a feature of this coil not known or even suspected by its maker. Why this great difference in the two sets of impulses? Is it due to the relative positions of the two primary windings, or, what is perhaps more likely, that the "break" in one does not take place at the best point of the wave? Whatever may be the reason I mean to have the weaker brought up to the level of the stronger—a reversal of trade-union policy—and thus eliminate causes for dissatisfaction with the performance of this X-ray set. I would also draw attention to the absence of secondary images such as we found when working with direct current. I think it will be agreed that this method of investigation with the slit and rapidly moving film has a very high value for our purpose, with the added merit of extreme simplicity, and yet capable of elaboration into one of great accuracy.

In addition to the points I have briefly indicated, it shows us that we can get sustained impulses by increasing the size of our coils; it also teaches us, so far as these huge coils are concerned at least, that we must revise our ideas as to the functions of the condenser. Instead of being a mere dissipator of energy, it is a reservoir, and by its oscillations gives rise to impulses through the secondary winding and the X-ray tube that result in useful X-rays. What I do not like about the system is the reverse impulses that must traverse the tube, to its detriment. Possibly these might be controlled by valve tubes, but this is a matter for future investigation.

These films also seem to support my view that our chief requirement for successful work is a supply of extremely high-voltage impulses more or less sustained. The higher efficiency of the coil up to the limit of its capacity is demonstrated beyond all question; and almost with equal clearness are the weak points of the transformer brought out—not the least of which is the failure of the voltage to rise with the increase of current, so that when we increase the current through the tube we do not get a corresponding increase of electron velocity.

I think it of the highest importance that we should come to some agreement as to the real cause—personally I do not feel competent to give an authoritative opinion, but I believe it to be partly due to the self-induction and impedance of the secondary winding. I am aware that this counts for very little in ordinary transformers, but there must be a point where it begins to exert a restraining influence on output, and in the class of transformers we are considering I believe we are well past that point. With the necessarily large number of secondary turns this impedance asserts itself long before the peak of the wave is reached, especially when drawing off a large current, so that by the time the peak comes into play—the only part of the wave for which we have any use—its influence is severely discounted. By suppressing the lower three-fourths of the wave we introduce the necessary element of shock and get that sudden rush of current characteristic of the coil, without its limitations.

There is another point that may be of even greater importance, and one on which I desire to have the opinion of physicists. The advantage of the sudden impression of a high-voltage impulse on the tube is that the initial rush of current has to be carried by a limited number of electrons which can do so only by virtue of a high velocity. The rest of the electrons come into action immediately afterwards, and as there are plenty of them their velocity falls. With the gradual rise of the transformer current all the electrons are brought into action by the time the peak of the wave comes into play, nullifying its influence in producing the high electron velocity so necessary for our purpose. If this theory is untenable I shall be glad to be put right, but it appears to harmonize with many of my observations. It is in accordance with this idea that I am of the opinion that a continuous current would be unsuitable, even if we could get it; also that there would be no advantage in having the impulses sustained beyond a very brief period—not unlikely I am wrong in speaking of sustained impulses at all in this connection, but at present I cannot help feeling that they might be given a just appreciable time factor with advantage. The interval between successive impulses need be no longer than sufficient to allow the electrons to come to rest. Most coils and transformers give impulses at the

rate of about 100 per second, but the films I have shown indicate that the interval is very long compared with the period during which useful radiation is taking place, and a much higher periodicity is permissible if it can be obtained. I consider it essential, however, that the electrons should be at rest at the moment the high-voltage impulse arrives.

As to the most desirable wave-form, a sudden abrupt rise to an extremely high peak is essential; what happens after is of no consequence whatever. It can produce only heat and useless radiation. As Fig. 8 shows, a gradual rise to the peak is hopelessly inefficient.

It being very generally agreed that a high electron velocity is essential for our purpose, we may with advantage consider the usual method of attaining velocity. Take the familiar instance of a golf ball; no golfer thinks of giving his ball velocity by means of a gradually increasing pressure—he gives it a smack! and he well knows that if the moment of impact does not synchronize with what corresponds to the peak of the curve the result will not be entirely satisfactory. This is one of the reasons why I consider the current should not flow until the voltage has risen to or near its highest point. The analogy may not be a very perfect one—few of them are, and I fear it recalls many painful memories—but it will serve. We may carry it a step further: The golfer occasionally finds his ball almost submerged in a pool of water, yet within reach. With doubtful wisdom he decides to play it without lifting under a penalty stroke. If you happen to be one of his companions in the game you will be more interested, for the moment, in what happens to the water than to the ball, and place yourself accordingly. I want you to do so now, imagining the water to be the electrons in the X-ray tube and the head of the club the high-voltage impulse. The instant the club meets the water the first particles are projected from the pool at high velocity, but as the club head gets further in the number projected increases and the velocity falls—in the end there is displacement of a large quantity of water at a very low speed. Applying this analogy to the X-ray tube, it is only the first impact that gives us the needed high electron velocity; nothing is gained by prolonging the impulse beyond a very brief period, and the sooner it is cut off afterwards the better. It further illustrates why I consider that anything in the nature of a continuous current would not suit us at all, as the electrons must be allowed to come to rest between successive impulses. Such electron velocity as would be produced by the flow of a continuous current at any practicable voltage would be too low to generate useful radiation. Just as in the drive at golf, the moment of impact is the only instant in the whole cycle that produces useful result, and I consider that investigations directed towards increasing the intensity and frequency of impact are most likely to lead to a realization of our desires. As to frequency, we may learn something from the film made by the "single flash" coil. "Single flash" is a misnomer—the film shows the "flash" to consist of at least 10 impulses, of which any number up to five produce useful radiation. The duration of the flash is said to be approximately 1/100 second, so that a frequency of 1,000 per second is quite feasible so far as the tube is concerned. I am now in a position to state what I consider to be the ideal current for radiological purposes: simply an intermittent current with a periodicity of 1,000 per second at a voltage equivalent to the first or even the second one of the series that make up the "single flash" I have shown. This will give us everything we can possibly want for any medical purpose—at least so far as one can foresee at the present time.

I am quite prepared for disagreement with my views. Let me say, however, that they have not been arrived at hurriedly; they are the outcome of years of experiment and thought on the part of one who has no axe to grind or any particular fad to push to extremes, other than to advance the science of radiology. Therefore I ask those who may feel disposed to dismiss my ideas as absurd or fantastic, first to give them careful consideration; I believe they will bear critical examination so long as it is free from prejudice.

I am quite alive to the fact that my views are rather severely critical of transformers of the Snook type, but I wish to repeat what I have said in my paper, that it is far from my wish to decry this class of machines. They have served radiology well, and some very fine results have been secured with their aid. The principles underlying the system are quite sound, and I believe an almost ideal X-ray generator could be made on the same lines. I do not approve of the way they are at present constructed, and I venture to say that the maker who has the courage to produce one designed in harmony with the views I have expressed, will score a triumph. Since first using one my desire has been to improve them, and never more so than at the present time; I regret to say, however, that I have found the majority of makers of X-ray apparatus reluctant to profit by the experience of those whose business it is to use these machines for the purpose for which they are intended. The science of radiology is still in the stage of development, and the time is not yet for conservatism or standardization.

[The discussion on this paper will be found on page 732.]

PROBLEMS OF INTERRUPTED AND FLUCTUATING CURRENTS.

By Major C. E. S. Phillips, O.B.E.

(*Paper received 24 January, 1920, and read at a Joint Meeting of* The Institution, The Royal Society of Medicine (Electro-Therapeutics Section), *and* The Röntgen Society, *26 February*, 1920.)

The velocity and quantity of the electrons in an X-ray bulb are the principal factors controlling the design of electrical apparatus required for radiography in all its numerous branches.

Since the potential difference between the electrodes of the tube determines the speed of the electron and therefore the quality of the X-radiation produced, the electrical problem resolves itself mainly into one of engineering.

The potential difference necessary is, however, exceptionally high, and the machines and appliances require to be specially designed.

Medical experience, for example, points to the need of an electron speed such that the resulting X-rays shall be as penetrating as the γ-rays from RaC. But even with a difference of potential of 170,000 volts between the electrodes of the tube we can only get a ray about half as penetrating as this.

Unfortunately the wave-length of the most penetrating γ-rays from radium turns out to be shorter than was originally anticipated, and recent experiments go to show that the minimum potential difference required to produce a similar ray from an X-ray bulb would be 600,000 volts. Even this figure can only be approximately hinted at; it may actually prove to be nearer 2,000,000 volts.

Possibly the great electrical difficulties thus foreshadowed may hearten the shareholders of radium companies, but it is nevertheless a disappointment to radiologists to find that the prospect of producing such a radiation is still far off. In addition to the requirements of medical practice there are other calls for highly penetrating rays; metallurgists are asking for a machine that will give 300,000 volts. For instantaneous radiography in medical institutes large currents are also needed at these high voltages, so that the demand in this respect is, in fact, always ahead of the supply. In some cases, the power put into the tube itself has exceeded 14 kw., or nearly 20 horse-power.

This represents one end of the scale. On the other hand there is the radiography of wood and a wide range of other uses necessitating only moderate electrical plant. There are also the needs of the Army and Navy, as well as many special applications, and it therefore becomes a question whether one type of apparatus can best fulfil all these requirements. It is, in fact, a large subject and difficult to generalize upon. In some cases the highest power is needed, and weight and portability are comparatively unimportant, whereas in other applications portability is the chief desideratum.

So far, the principle of electrical induction provides the most practical way of producing the high-tension electricity for X-ray work, but let us not be neglectful of other possible means. If we now look mainly to electrical engineers to solve the difficulties connected with the large-scale production of electricity for this purpose, there is still much left for the physicist to do in trying to improve still further the X-ray tube itself. We must find some new plan whereby the energy supplied to the tube will reappear as X-radiation rather than as heat radiation. At present the tube is the most inefficient part of a modern high-power outfit.

Whatever differences of opinion the discussion may bring out as to the merits of this or that scheme of work, it is clear we shall agree at least that all present-day methods are complicated, and usually wasteful. We shall also probably agree that for work requiring a large expenditure of energy the alternating-current transformer meets the case better than any other apparatus so far devised.

One outstanding feature of the induction coil, however, is the suddenness of the rise of secondary potential to a sharp maximum when the primary current is broken. This gives less heat in the tube and is a great advantage over the more rounded peak of the secondary potential curve obtained with an alternating-current transformer. I shall refer again to this later on and venture to suggest a plan by which the transformer may be persuaded to imitate the coil in this respect. But first I should like to refer briefly to coil design.

The induction coil has much to recommend it. The simplicity and absence of moving parts are great advantages. In reality the interrupter is the "fly in the ointment" here, for therein lies our principal limitation, and our troubles are divided between it and the condenser. Curiously the shape of the condenser is of importance, for of two condensers with the same capacity the one having long narrow leaves is not so effective as one in which the leaves are nearly square. I do not remember to have seen this question referred to previously, and it will be interesting to know what has been the experience of others.

It must be borne in mind that electricity supply is not universally on the alternating-current system, and an a.c. generator is an expensive addition to an already costly outfit. For smaller installations the coil will hold its own for a long while yet, I think, and attention should be given to its design, and especially to the question of the improvement of interrupters. One of the causes of coil breakdown during the war was fracture of the wax during transport. It is suggested that a fairly thin oil could be used as an insulator, thin enough to draw off before transport, and it should be possible to replace the oil without creating air cavities. The

secondary could be wound with No. 36 aluminium wire and thus save one-third of the weight of copper. An improvement from an Army point of view could also be effected by using a removable core. A coil so designed would be extremely portable on account of the distribution of weight. From what has been seen of captured German X-ray apparatus used during the war, it appears that the question of dividing the several sections of the outfit, so that many small transport cases are used instead of a few very large and heavy ones, has received careful attention. If aluminium wire is used there is no need to increase its thickness owing to inferior electrical conductivity as compared with copper, because the current-carrying capacity of No. 36 copper wire is already well in excess of what is actually required. It would seem, in fact, desirable to use more turns of a thinner gauge so as to obtain a higher potential difference at the secondary terminals, but experience shows that for some unknown reason No. 36 is the best size.

The weakest point of a coil outfit is undoubtedly the condenser. Since the end of the war dozens of coils have been returned from France quite sound in all other respects. I would suggest that an alternative path should always be provided to carry off any excessive surges of current into the condenser. Recent experiments in this direction at the War Office X-ray laboratory have shown that a condenser, while in use, may be short-circuited through a water resistance (3 inches of tap water using fine copper wires just dipped below the surface) with only a reduction of 20 per cent of the coil output. When an oscilloscope tube replaced the water, no appreciable loss of output was noticed, although the vacuum tube lighted up brightly. Its life was short. Finally, three 16-c.p. 250-volt carbon-filament lamps in series joined across the condenser terminals proved quite satisfactory.

The filaments glowed a dull red, and irregular surges of current were indicated by momentary brightening of the lamps, but there was no appreciable reduction of coil output and the plan will, I hope, reduce condenser breakdown in future to a minimum.

Now the value of the interrupted current that may be safely used with a coil is limited owing to the flare when the primary current is broken. Interrupters are frequently imperfectly designed and constructed. Experiments with tantalum blades are required, for in tests already made there is indication that flare can by this means be reduced. It is interesting to notice that, although tantalum is not "wetted" by mercury, it nevertheless gives a perfect contact. The arc at break occurs in that case between the practically non-vaporizable tantalum and the mercury, and the speed of the motor assists in giving a sharper interruption of the circuit. In other cases the high surface tension of the mercury determines the suddenness of the rupture.

The behaviour of an interrupter may be conveniently studied by screwing a cup-shaped vessel into the body of the apparatus and stretching over its wide mouth a small sheet of thin rubber. The pulsations of this for variable gas pressure within can be communicated to a suitably light lever system and records taken upon a revolving drum. Experiments at the War Office X-ray laboratory show that undue flaring is immediately detected by this means, and comparisons may readily be made. Absence of flare is also necessary to ensure the efficient action of the mechanical rectifier. An attempt is being made to design an interrupter that will break 20 amperes quietly and continually without overheating. I wish to emphasize the importance of accuracy in the construction of interrupters and to direct attention to the need of careful alignment of all symmetrical parts. It may also be appropriate to refer briefly to the constant high-tension machines made by Messrs. Evershed and Vignoles and to see what prospect there is of utilizing them for the generation of X-rays.

The maximum potential difference obtained so far with any one small machine is 2,500 volts, and the usual practice consists in linking up three machines in series, each to give 1,800 volts. Thus a set for laboratory use gives about 5,000 volts, the potential difference being directly proportional to the speed. An output of 15 milliamperes can be obtained in this way, but insulation difficulties at higher potentials seem to exclude the possibility of developing this plan for X-ray work.

Passing over the question of measuring instruments, I come finally to some notes upon the transformer. Most of the discussion that is to follow will probably centre mainly around this means of supplying the X-ray tube with energy on a large scale. The design of transformers has reached a high degree of perfection. Their electrical efficiency is remarkable, but where very high-tension work is concerned (such as in X-ray technique) and a rectifying disc is spun by a synchronous motor, the weak spot of the installation practically always seems to be the insufficient guarding of the armature windings from induced surges of current. But with the rectifier out of action the plant is useless, and it is hoped that this vital point will receive attention during the discussion. Earthing through a condenser, or other means of assisting the insulation of the armature to withstand the strain put upon it, is essential. The reliability of this type of apparatus in skilled hands is, however, remarkable. I know of one institution where over 60,000 radiographs have been taken during the war with a large outfit, and the apparatus is still in perfect working order in spite of the fact that about 40 milliamperes were used for each exposure.

One serious objection to the transformer arises, however, from the form of the secondary P.D. wave. The behaviour of an X-ray tube appears to show that the electrons are not instantly fired out from the cathode on the application of the potential difference to the electrodes. Where a coil is used, the potential difference rises so rapidly to a maximum that there is not much time for the electrons to be shot out before such a potential gradient is created that their speed is high and their number considerable. The slower rise and fall as indicated by the shape of the transformer P.D. curve give time for electrons to be ejected at speeds too low for useful X-ray work, and thus the target is heated by impacts that merely waste their energy in heat.

It is generally agreed that a steeper P.D. wave is required with transformers, and I venture to suggest a plan whereby this may be obtained for any given installation. In 1895, and about six months before the

discovery of X-rays, Messrs. Barr, Beeton and Taylor published a paper in the *Electrician** dealing with the question of changing the shape of alternator wave-forms. They keyed to their experimental alternator a special commutator called by them an "injector," by means of which inductance or capacity, or both, could be introduced into the circuit at regular intervals. In this way remarkable distortion of the original wave-forms was obtained without sparking.

In 1911 another experimenter constructed an alternator that gave a sharp peak on one side of the zero line and a suppressed loop on the other. It was found to work well. But in actual practice the power has almost invariably to be taken from a main supply and we have to make the best of the wave-form given by the generating station. This is governed by several factors, the shape of the pole pieces in the alternator, the arrangement of the armature coils, etc., but it is never an accurate sine wave and generally rises first quickly, then tends to flatten a little, and finally rises more rapidly to a rounded peak and falls symmetrically. It is therefore suggested that this wave be distorted synchronously by keying an "injector" to a small synchronous motor and connecting it in series with the main supply and the transformer. In this way a wave-form could be obtained which would render the rectifying disc unnecessary. The installation would not only be less costly, but weigh less, occupy less space, and be highly efficient for the requirements of X-ray technique.

* *Electrician*, 21 June, 1895, p. 257.

[The discussion on this paper will be found on page 732.]

HIGH-TENSION TRANSFORMERS FOR X-RAY WORK.

By Russell S. Wright, Member.

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There are probably very few scientific instruments on which so little systematic research work has been accomplished as the subject of this paper. We have not yet even reached a satisfactory classification as regards either output or efficiency. As regards induction coils, which are of course a definite type of high-tension transformer, we have these as a rule merely catalogued by spark length and occasionally advertised as "Intensified," a wonderful phrase suggesting that the instrument has been accorded some special treatment which mysteriously increases its output.

In the case of an induction coil especially it may be admitted at once that the problem is a difficult one. We are dealing, not with a continuous output, or even a sinusoidal wave, but with a succession of "peaked" oscillations of varying wave-form and varying periodicity, interspersed with an "inverse" discharge which must be eliminated, and in the elimination of which some of the useful output is bound to be similarly absorbed.

An advance upon the spark-gap method of measurement has undoubtedly been taken by stating how many milliamperes a certain coil will pass through an X-ray tube of a given alternative spark-gap, but this classification is still anything but satisfactory. It is quite certain that, not only does an ordinary moving coil milliammeter not measure either the peak value of the discharge or what is known as the "root mean square value," but the reading indicated may vary with different types of milliammeters and also with induction coils of varying wave-form, interrupters of different patterns, etc.

Our science will never rest upon a sure foundation until we can accurately rate both an induction coil and a closed circuit high-tension transformer in terms of their value to the radiologist, just as we can give a galvanometer a definite "figure of merit" or ascribe a certain "numerical aperture" to a microscope objective.

In approaching the problem, it is both an advantage and a disadvantage that "efficiency," as understood by an electrical engineer, matters little or nothing. I have never yet met the radiographer who cared in the very least about his electric current consumption, as the factor is a negligible one compared with economy of time, tubes, plates, etc. This, as I have said, is in one sense a drawback, as it renders any figures based upon "input" absolutely valueless, the least efficient instrument from an electrical standpoint being possibly the most valuable from that of the radiologist. The present very humiliating position is that we know next to nothing of the whole subject. We do not yet know, for example, whether a succession of high-peaked waves is better or worse than a smaller number of oscillations longer maintained; neither do we know as yet whether the tops of the peaks only are of value, or whether outputs of lower potential play their parts as well, possibly in bringing out details of the softer tissues of the body.

In the case of an induction coil, I am not convinced that we have, as yet, any means of ascertaining what the peak value of our discharge really is, as it is quite certain that the point of highest potential is only maintained for an exceedingly short interval of time, and it is, I think, a very doubtful point whether any recording instrument at present available will really measure it. There seems every indication that the wave-form most suitable for radiography is not equally so for therapy. If this be the case, the question arises as to whether one instrument can be made from which outputs of sufficiently variable wave-form can be produced at will, or whether two instruments, one for radiography and one for therapy, are necessary; or even whether the same type of discharge is always suitable even for, say, radiography alone. Do we, for example, want the same wave-form (apart from questions of milliamperes and potential) for the radiography of (1) a hand, (2) a bismuth meal, (3) a section of steel? If not, what variations in wave-form are required, and can they be obtained from the same instrument, and by what means? These are questions on which the manufacturer has at present no definite information on which to work, and our ignorance of what is really required is at present a bigger obstacle to progress than the corresponding problem of how to obtain it.

I have no ready-made solution to offer, but I would suggest that the time is now ripe for a definite move forward, and that radiologists, electrical engineers, and physicists should, so to speak, come into partnership in the attempt to solve a very baffling problem, and I would further suggest that the British Scientific Instrument Research Association is the proper body to co-ordinate and direct the work of the three so as to produce reliable results.

In the case of the so-called high-tension transformer —and I think it would be well if the term were by consent not applied to the piece of apparatus known as an induction coil—the problem is a simpler one, as we are at all events dealing with a curve of sinusoidal character, somewhat modified and even distorted, it is true, but still essentially sinusoidal.

In the original interrupterless machine as introduced by Snook, we had in fact a real sinusoidal curve with every alternate wave inverted as shown in Fig. 1. In

the modern machine, however, the curve has been somewhat modified and is no longer strictly sinusoidal or even symmetrical, but may be represented as in Fig. 2. It is fairly certain that the direct measurement of such a current by means of an ordinary moving-coil milliammeter is both more correct and more consistent than is the irregular discharge from an induction coil, where the wave-form tends to vary with the condition of the interrupter, the adjustment of the contacts, and various other causes.

It is a matter of common knowledge that the conditions

FIG. 1.

of work with an interrupterless machine can be more exactly reproduced from day to day than is the case with an induction coil, and equally certain, I think, that the readings of the milliammeter are more reliable; though again it is a matter of common knowledge that a milliampere from an average coil is more effective from a radiological point of view than one from an interrupterless machine, probably, I think, because in the former case the *real* current is much more than the instrument indicates.

A closed-circuit transformer also adapts itself far

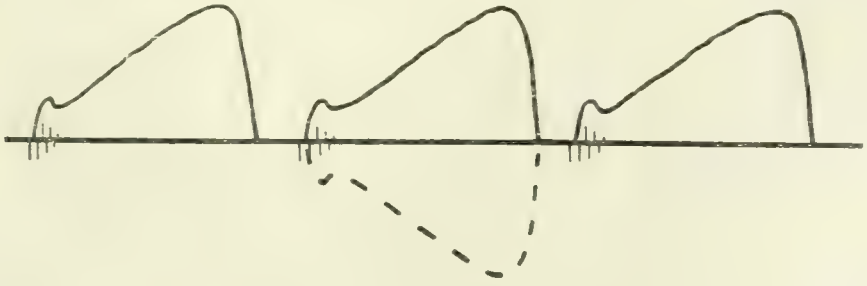

FIG. 2.

better to the indirect measurement of its output than does the induction coil, for the simple reason that its electrical efficiency is far higher and more easily computed. This question of efficiency, as I have pointed out before, is absolutely unimportant in one sense, but if it can be ascertained—and in the case of an alternating-current transformer this can be done with fair accuracy—it assists enormously in calculating the secondary output.

I should be inclined to suggest, therefore, that an alternating-current high-tension transformer be taken as the basis on which to work, and that an attempt be made to classify induction coils according to their effective outputs for the purpose of the radiologists and compared with a transformer of standard size and efficiency.

Assuming, therefore, that this suggestion is accepted, how should a transformer be rated? Before deciding this, it must be borne in mind that what to an electrical engineer is a big overload is to the manufacturer of X-ray apparatus a normal condition, as in X-ray work machines are in practice only used to their full output for a fraction of a second at a time. An overload rating is therefore, I think, perfectly justifiable, and our earlier machines were so rated by about 100 per cent; but when a machine was put on the market by an enterprising foreign firm rated at an overload of well over 1,000 per cent, I felt that the position was getting ridiculous, and I notice that now practically every responsible firm refrains from mentioning outputs in kilowatts at all.

It is, however, essentially a question for an authoritative decision, and I think that the joint societies here represented might well pronounce their opinion as to what extent overload may be allowed in estimating outputs of what are known as "interrupterless" machines. Reverting to the question of wave-form, manufacturers still want to know just what is required, and so far we have not been enlightened. For example, we are told one day that "peaked" waves are what is required, while the next day we are confronted with a demand for auto-transformer control, the effect of which, as every electrical engineer knows, is in most cases to flatten the wave-tops as compared with

a transformer controlled by an ohmic resistance. Auto-control undoubtedly has great advantages when working with a Coolidge tube, but we shall not get so peaked a wave; which do medical practitioners want?

There is one more point I should like to raise in connection with both induction coils and high-tension transformers, and that is the question of security against breakdown. It must be admitted that the "life" of one of these instruments is far less than it was ten or even five years ago, and few of the equipments being turned out to-day will permanently withstand the strain of modern conditions. The continual use of a coil for "deep therapy" is undoubtedly the most prolific cause of breakdown at the present time, and has raised problems which have given manufacturers a good deal of anxious thought.

If one considers that an output of, say, 3 milliamperes at a 12-in. spark-gap from an instrument capable of giving, say, 100 milliamperes, means that it is kept at a high potential on practically open circuit for long periods at a time, one will realize at once the problem that we are up against. Examining the exposed end of a secondary winding in this condition, we can see that it is in a constant state of effluve and that the discharge is literally spitting away in all directions.

It is impossible to look at this effluve without feeling that sooner or later the insulation is bound to go, and go it invariably does if the strain is continued long enough. Just now the position is made worse by faulty material: wax that is not wax, paper that is not paper, and copper wire that is not up to pre-war standard does not help the situation, but in any case I am convinced that a coil or transformer, constructed to give a heavy output for radiographic work, and with dry insulation, cannot be continually used for deep therapy without the risk of trouble.

Various devices can be used to safeguard more or less the end windings, but the only real remedies are two: either we must wind an instrument for deep therapy alone, or we must adopt oil insulation. The former course entails the radiologist installing two pieces of apparatus, viz. one for therapy and one for radiography. The latter will do all the work with one, but will be heavier, larger, more difficult to transport and more expensive.

Again we should like guidance from our medical friends; shall we concentrate on oil insulation or would they prefer two separate instruments? In answering this question the problem referred to before as to whether the same wave-form is needed for both purposes must not be overlooked. These are definite problems, and I have ventured to put them forward, as their solution or partial solution will do much to place the industry upon a more satisfactory footing than it is at present, and I commend them therefore for the consideration of members.

Discussion on the Papers by Dr. Morton, Major Phillips, and Mr. Wright, read at a Joint Meeting of The Institution, The Royal Society of Medicine (Section of Electro-Therapeutics), and The Röntgen Society, 26 February, 1920.

Professor W. Salomonson: The high-tension transformer has in many cases taken the place of the induction coil in the Röntgen laboratory. This is nearly always to be found when an unlimited supply of electricity is available, in the form of either direct or alternating current. Only for purely therapeutic purposes the induction coil still largely maintains its original position of supremacy over the closed iron-circuit transformer. If we try to ascertain why this should be so, we have to consider many questions. The first is the problem of the very-high-tension generator. In radio-therapeutics the required pressure is generally extremely high; we want to use only the most penetrating X-rays. In the induction coil we have a double transformation, firstly from a low-tension interrupted direct current to a higher-tension alternating current. This is properly a deferred transformation. Secondly, this alternating current of peculiar form is transformed into a pulsating current of extremely high potential. The first transformation asks only for an insulation of the primary circuit to stand some 2,000 volts. The second transformation needs an insulation of the secondary circuit to stand at least 200,000–300,000 volts according to the spark length, the transformation ratio being something between 150 and 300. With the closed iron-circuit high-tension transformers we have generally a rate of transformation of between 600 and 1,200. If the transformer is to be used for therapeutical work, and especially for deep-seated radiations, we must be able to get at least 250,000 volts from the secondary terminals. This means nearly always that a very large number of secondary windings have to be compressed into a narrow space. The difficulties of a satisfactory insulation then become very great and render such an instrument very costly, much more costly than an induction coil where the secondary windings can be distributed over a much larger space. A breakdown of the insulation means costly and difficult repairs with both instruments, but, just as an induction coil can easily be produced at less than half the price of a high-tension transformer, so it is also with the cost of repairs with both instruments. Though a few radiologists seem to prefer the transformer to the induction coil for therapeutic work, I feel sure that the induction coil will not be supplanted by the transformer for the production of very penetrating X-rays. As in radiography we need only very penetrating rays in metallo-diagraphic work, we can expect that for general

radiographic and radioscopic work the transformer will be preferred. The construction of a closed iron-circuit transformer with a secondary voltage of 100,000 does not offer too much difficulty; it meets every requirement in general work except the production of the most penetrating rays, and in its present form a breakdown of the insulation rarely occurs. If we use it in preference to an induction coil we have only to consider its efficiency. Of course, there are some minor points, such as the ease of working, the form of the secondary current waves and so on, but I think all these points are of secondary interest. The question of the wave-form has still some interest with gas-filled tubes, but not with the Coolidge tube. Only the question of efficiency remains. A few years ago, in a paper before the Röntgen Society, I described some methods of measuring the efficiency of an induction coil. Later on I worked out another method which, I think, is a distinct improvement on the former ones. The whole secondary output was again transformed into heat, and the number of calories generated per second was carefully measured. The resistance in these experiments was simply a glass tube through which water flowed in a steady current. The temperature of the water was taken before and after the passage of the secondary electric current, as soon as a state of thermal equilibrium was reached. Ordinary mercury thermometers could not be used as they were spoiled by internal glow-discharges. Therefore I had a series of alcohol-filled instruments made in Amsterdam divided into tenths of a degree C. and very carefully calibrated. The construction of these instruments caused some difficulty, as the divisions were not equally distant in different parts of the scale. But after some trouble I got a set of instruments agreeing well within one-tenth of a degree C. with a standard mercury thermometer over the whole scale. The measurement of the water flow also proved to be less simple than I thought at first, but it was also worked out in a very simple and reliable way. The correction for loss of temperature during the experiment proved to be very simple. With this new apparatus, which was entirely insulated from the earth, and in which any desired resistance could be inserted with the greatest ease by putting in a new glass tube of appropriate dimensions, I measured the secondary output of some induction coils under different working conditions, whilst wattmeter readings were taken for the input. As the primary and secondary currents were measured with hot-wire instruments the copper losses could be taken into account.

For the high-tension transformer I was able to use a much simpler method. The secondary terminals of one transformer were connected to the secondary terminals of another transformer. In this way the first was used as a step-up transformer, the second as a step-down transformer. The input of the first and the output of the second were both measured with a wattmeter on the low-tension side. A hot-wire milliammeter was inserted in the high-tension circuit, and instruments of the same kind in both low-tension circuits. The resistance of the primaries and secondaries being known, the copper losses could be calculated. The iron losses were calculated on the basis of an equal division between the two transformers. I have also used this method with three induction coils. I will give a few figures for alternating current of 50 periodicity:

TABLE I.

(1) *Oil-insulated Transformer by Snook.*

Input	Efficiency	Output
2·98 kw.	0·903	2·69 kw.
2·02 ,,	0·882	1·78 ,,
1·10 ,,	0·864	0·95 ,,

(2) *Dry Transformer by Koch and Stertzel.*

2·83 kw.	0·890	2·52 kw.
1·92 ,,	0·870	1·68 ,,
1·01 ,,	0·854	0·86 ,,

(3) *Induction Coil by Max Kohl; 12-inch Spark Lengths.*

970 watts	0·809	785 watts
840 ,,	0·790	663 ,,
553 ,,	0·791	438 ,,
222 ,,	0·788	175 ,,

(4) *"Instantacoil"—16 inch.*

970 watts	0·788	764 watts
807 ,,	0·801	646 ,,
501 ,,	0·799	400 ,,
222 ,,	0·767	170 ,,

(5) *Therapeutic Coil, Siemens-Halske.*

807 watts	0·757	610 watts
618 ,,	0·771	476 ,,
501 ,,	0·775	378 ,,
347 ,,	0·764	267 ,,

With the transformers the efficiency is not quite so large as we might expect, but both instruments were among the first made for X-ray work. In both, the quantity of iron is considerably less than we might expect in a 4-kw. transformer. I suppose that the newer transformers would yield better results, otherwise the figures are normal in this respect, that they show a better efficiency with a higher input. With a quarter load these are still appreciably better than 85 per cent. With induction coils the results are more irregular, and I have not been able to trace the cause for it. The smallest coil gave the best results. Probably this coil was loaded up to its fullest capacity, whereas the "Instantacoil" was loaded to scarcely more than half the maximum capacity, and the large Siemens coil to not more than perhaps one-quarter load. Perhaps we have also to consider the fact that the last-named coils were much better insulated so as to be able to give at least a 16-inch spark. The Siemens coil is used every day during at least four hours working on a very hard Röntgen tube with a parallel spark of more than 12 inches.

The induction coil used as a transformer has an efficiency of between 0·75 and 0·81 per cent. We hardly ever use a coil in this way: it is practically always fed with an interrupted current; and in this

case we get very different figures, depending on the way the coil is used. With the coil working on a water resistance, absorbing both the secondary impulses, the closing as well as the opening impulse, I found the figures given in Table 2.

TABLE 2.

Small Coil by Max Kohl—12 *inch.*

Primary Input	Secondary Output	Efficiency
74·3 watts	50·3 watts	0·677
130·0 ,,	92·7 ,,	0·713

"Instantacoil"—16 *inch.*

63·2 watts	49·0 watts	0·776
84·3 ,,	66·4 ,,	0·787
127·0 ,,	96·1 ,,	0·757
201·0 ,,	154·1 ,,	0·767

The "Instantacoil" with its large iron core gives better results than the smaller coil, the mean figures for the larger coil being 0·77, and for the smaller coil 0·70.

With the Morton rectifier in the secondary circuit I obtained the figures given in Table 3.

TABLE 3.

Small Coil—12 *inch.*

Primary Input	Secondary Output	Efficiency
34·0 watts	19·3 watts	0·568
60·9 ,,	36·4 ,,	0·598
122·7 ,,	74·9 ,,	0·610
167·5 ,,	105·0 ,,	0·637
232·2 ,,	157·3 ,,	0·678
282·6 ,,	198·5 ,,	0·703

"Instantacoil"—16 *inch.*

82·2 watts	49·8 watts	0·606
92·6 ,,	89·8 ,,	0·600
126·4 ,,	75·2 ,,	0·595
159·0 ,,	95·1 ,,	0·598
417·4 ,,	274·0 ,,	0·633

All these figures were obtained at the primary and secondary terminals, and represent the efficiency of the coil alone. They are therefore somewhat misleading. We ought to consider the coil together with the interrupter. We then find for the Max Kohl coil the figures set out in Table 4.

TABLE 4.

Input	Output	Efficiency	Interruptions
343·5 watts	185·7 watts	0·540	126·0
350·8 ,,	183·2 ,,	0·522	112·0
387·1 ,,	193·0 ,,	0·499	110·0
535·7 ,,	212·5 ,,	0·397	79·0
587·0 ,,	208·0 ,,	0·354	74·0

The efficiency is better with a high rate of interruptions than with a smaller number. The smaller the current broken in the interrupter, the better is the efficiency of the combination. A very large amount of energy is absorbed in the interrupter, and the more so the greater is the current strength at the moment of the interruption. I suppose that, especially with stronger currents, a short arc is formed at the contact which absorbs a good deal of the primary energy. It does not seem improbable that some means can be found to lessen these interrupter losses.

Professor C L. Fortescue: As a radiologist, my experience is practically *nil*, but I have been in touch with developments in the last few years that may have a great influence on the future of radiography. The papers of Dr. Morton and Major Phillips have brought out one outstanding point, viz. that for practical X-ray work the demand is for the highly penetrating rays produced by the quantity of electricity which passes through the tube at the high voltage. They have shown us that it is useless to pass a large quantity of electricity through the tube if the voltage is low: it only leads to overheating. Whether we use a coil or a transformer, some part of the discharge is at a high voltage, and some part at a low voltage; but if we use, by a method which has been developed recently for wireless telegraph purposes, a hot-filament rectifier and a condenser, I think it is possible that the whole discharge through

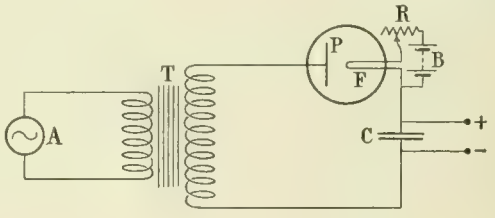

FIG. A.

the tube—at any rate through a Coolidge tube—could be at the high voltage. A point raised by Mr. Wright was that the low-voltage discharge was also essential, but that point I am not in a position to discuss. I can only suggest methods whereby for a Coolidge tube a high-voltage discharge can be obtained. For wireless purposes, we have latterly used for the generation of high-voltage direct currents from alternating-current supplies the circuit shown in Fig. A (which is taken from a paper before the Physical Society of London*). The rectifier is almost the same as a Coolidge tube. F is a heated tungsten filament, supplying us with a source of electrons, and P is the plate to which those electrons will pass when that plate is at a positive potential with respect to the filament. C is a condenser, on one side of which the positive charge collects after the passage of the electrons. On the other side of it will be the corresponding negative charge. The action of the rectifier is as follows: The filament is surrounded by a mist of negative charges and during the half cycle of the alternating voltage, when the plate is positive, by the ordinary rules of the attraction of a positive body to a negative body, that charge will be drawn away and will pass across the very high vacuum space between the filament and positive electrode. In the course of the alternating cycle in which the plate is negative, the action of the negative plate on the free electrons round about this filament is one of repulsion,

* *Proceedings of the Physical Society*, 1919, vol. 31, p. 319.

and consequently no current will pass so long as the vacuum is high enough to prevent a discharge of the usual kind. The result is that in spite of the alternating nature of the power supply, a negative charge will be lost from the upper plate of the condenser, which will be equivalent to giving that plate a positive charge.

Fig. B shows, diagrammatically, the action which takes place. The round-shaped wave is the wave of the voltage given by the transformer. The full line which is zig-zagging across the dotted line is the voltage

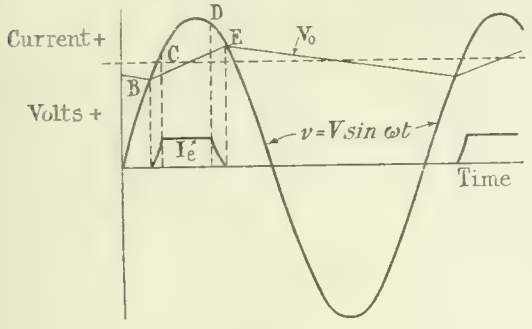

FIG. B.

that is available as a steady, or nearly steady, supply from the condenser C in the previous figure. When the voltage of the alternating current rises above this steady value, there will be a conduction of current through the vacuous space inside the tube.

The curve in Fig. C gives some idea of the actual tube efficiency that can be obtained with a rectifier of this kind. It will be noted that it is possible, by a suitable proportioning of the variables, to obtain something like 85 per cent efficiency in ordinary wireless practice.

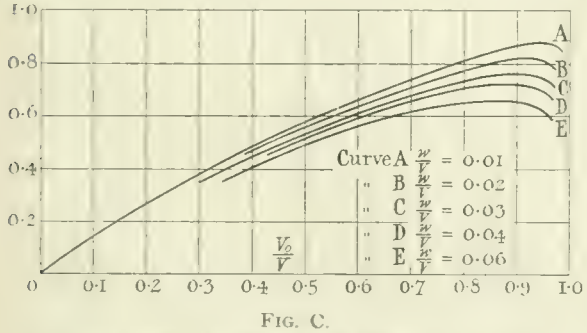

FIG. C.

V = peak voltage of alternating current supply.
w = filament watts required for 1 ampere of electron emission.

That is at a lower voltage than radiologists require. At the voltage with which radiologists work, the efficiency could be raised to about 90 or 95 per cent. I suggest that this is a poss ble means of securing a steady high-voltage supply for use with a Coolidge tube. There is a difficulty, which will probably suggest itself to many minds, namely, that the tube itself is subjected to the voltage of the condenser, plus the half-wave of the transformer when the latter is in the non-conductive direction. This is a very severe strain on the insulation. I understand that a very large number of radiologists make use of the Snook machine, and it is conceivable that with the combination of rectifier valve—and by the term "valve," I mean a high-vacuum hot-cathode valve, not the gas valve which has been already spoken of—and Snook machine, that difficulty would be overcome, and there would be available a source of current which would be operative at a constant voltage, and not at the variable voltage given by the Snook machine as used in the ordinary manner, or as given by an induction coil. With all deference to Major Phillips, I must point out that in America, in 1915, hot-filament rectifying tubes were in use capable of rectifying as much as 200 milliamperes, and working on 180,000-volt circuits. The experience I have had personally of rectifiers for this purpose does not go as far as that, or anything approaching it. The highest voltage I have had occasion to work with is what, by radiologists, would be regarded as ridiculous, namely 7,000 or 8,000. In the course of that experience I have never heard of a rectifier tube which gave any trouble owing to the high reversed voltage. Trouble has occasionally occurred owing to the valves being overloaded in the conductive direction, but it is easily overcome and would not be a serious difficulty for X-ray work. One further point arising from the demonstration which Mr. Wright has given: the "brushing" from a high-voltage supply is a difficulty which every wireless engineer has experienced, and I would suggest to the Electro-Therapeutics Section of the Royal Society of Medicine that they should discuss this question of high voltage and brush discharge with wireless engineers who have to deal with voltages of 100,000 under very adverse conditions. The difficulty is overcome to a great extent by a careful study of the elementary laws of electric fields.

Major G. W. C. Kaye: I should like to point out to those who are not radiologists how the present situation has arisen. X-rays were discovered by a physicist: they were promptly handed over to the medical profession not all of whom sought that co-operation with the physicist which might have been good for both parties. Latterly, I think, the situation has changed for the better, and the position now is, that radiology is hampered by lack of units and standard methods of measurement. There is, for example, no kind of standard or unit of radiation. The Röntgen Society is devoting some attention to that matter, and perhaps we shall hear of a solution before long, but we have not got a practical unit at the present time. The radiologist's methods of measuring current through the X-ray tube are, as has been pointed out already, extremely ineffective. He does not, as a rule, know the wave-form either of voltage or of current. Again, not one radiologist in a hundred ever takes the trouble to measure properly the voltage across his tube. The average radiologist does not know, sometimes within several hundreds per cent, what voltage he has on his tube, contenting himself, as he does, by measuring the spark between points. As the American Institute of Electrical Engineers has shown, the ordinary point gap may have 300 or 400 per cent of error as regards voltage, at any rate on large gaps. They have also shown that if we want to measure high voltages accurately the handy way is to use a sphere gap, and we must use

spheres as big as the maximum gap we are going to employ. I doubt if there is a radiologist in Great Britain who is doing anything like that. Very few of them even are using sphere gaps. I have gone into the question of measuring peak voltages on sphere gaps, and I found that Dr. Russell had anticipated all that I could have thought of doing in that direction. What the radiologist does need more than anything is the co-operation of the physicist and of the electrical engineer, who are used to measuring things. We shall never make any progress unless we can get them interested in radiology, and that is what I hope will emerge more than anything out of this meeting. In conclusion I should like to point out that the kind of efficiencies we are using in the X-ray world are such as to appal the electric engineer. We start by using either a transformer or a coil—a transformer with an efficiency of the order of 90 per cent or a coil with an efficiency of the order of 50 per cent. The efficiency of an X-ray bulb is something of the order of one part in 1,000. In a coil-driven tube I suppose something like 20 per cent of the rays are useful rays; the rest are of no use; in the case of a transformer-driven tube perhaps 10 per cent is a fair figure. So with either method of exciting the bulb, the final efficiency is something of the order of one part in 10,000. It is time for us to put our heads together and improve that state of affairs.

Dr. A. E. Barclay: It is common knowledge among X-ray workers that the current from the high-tension transformer differs widely from that produced by the coil. The heating of the tube by the high-tension transformer is out of all proportion to the X-ray output; and the number of milliamperes through the tube is no indication of the efficiency and character of the discharge from the tube. From high-frequency apparatus connected to the high-tension transformer the discharge is almost entirely of a brush character. There is an extraordinary tendency of the high-tension transformer current to leak and char such substances as vulcanite. I have brought a series of records of the impulses from various types of X-ray apparatus, made by passing a double-coated film rapidly below a slit in a sheet of lead above which the X-ray tube is in operation. The rate at which the film is passed through, by hand, increases in each case, and it will be noted how the gap between each impulse widens out in consequence of this. There is one feature of this film which calls for comment—there are streaks across in various parts of the band, and exactly identical streaks were noted in another record in which an aluminium filter was interposed. These bands were not noted in any other of the records. The records show that the impulses from the coil actuated by a mercury break give instantaneous radiographs with a time factor that is too infinitesimal to show even when the film is travelling at the rate of 40 ft. a second. Good records were obtained even with $\frac{1}{2}$ milliampere passing. In the high-tension transformer records the wave nature of the impulse is well shown, and also the fact that the time factor during which the tube is in operation is very considerable. The efficiency of the small impulses from a coil is most marked, and suggests that it is the sharpness, the bang, of the impulse that is responsible for the comparative efficiency of the discharge in comparison with that of the high-tension transformer. In the case of the latter machine the suggestion is that it is the duration of time during which the current is passing that is responsible for the heating of the tube. The comparison of milliamperes obtained from the coil and the high-tension transformer is no guide whatever to the efficiency of the two types of machine: the number of milliamperes is a complete fallacy in X-ray work as a guide to efficiency.

Mr. R. C. Clinker: There are several points in Dr. Morton's paper in which I was very much interested purely as an electrical engineer. With regard to the question of what is shown by the oscilloscope, I should like to know whether it is intended to show the voltage or the current that is supplied to the tube. It seems to me that it is very necessary to separate the meanings of the words "voltage" and "current" before we can get any clear idea of what we want. I notice in part of Dr. Morton's paper that he first uses the word "current," then the word "voltage," and later on the word "current" again. Fig. 1 (page 720) shows a very high peak given by the coil in the positive direction, followed by a small peak in the negative direction. If that is voltage produced by the coil I do not think it can be correct, because there is one thing we can say definitely about the induction coil, and that is, that the area of the voltage wave on the positive side at "break" must be equal to the area on the other side at "make." I do not say the maximum; I say the area. The maximum at "make" is, of course, very much lower, and we require it as low as possible. There is a further point with regard to the comparison that Dr. Morton shows between the induction coil and the transformer. I made an experiment a year or two ago with a Coolidge tube supplied from an alternating-current source with a synchronous mercury interrupter, and it gave a very interesting result, which I think is rather to the point in the comparison between the induction coil and the transformer, although it was a coil only that I was using. I started the apparatus up and I first connected it to the tube in the correct direction, that is to say, when the "break" occurred the target was made positive. The current through the tube was $2\frac{1}{2}$ milliamperes, and there was a bright illumination of the fluorescent screen. Then I reversed the primary current, so that the "make" voltage was applied to the tube is such a direction as to make the target still positive. The result was that 10 milliamperes passed through the tube in the correct direction, but there was no illumination at all upon the screen. That shows very clearly the difference between a very high peak wave and a wave of a very low peak, but lasting much longer. We have four times the mean current passing through, yet we have absolutely no illumination at all, whereas in the other case, with the smaller current, we get a bright illumination. I was using a Coolidge tube in which I could of course adjust the filament current to any desired extent, but the readings were taken at the same heating. There is an additional fact, which, I think, illustrates in a different way Dr. Morton's point—namely, that a Snook type of apparatus,

with rotating rectifier, with which I am acquainted, gives no screen illumination at all below a 2-inch gap, and I take that to mean that the voltage does not help medical men until it gets far above that gap. So that what we want is a high voltage, and we want the current through the tube to be passed at that high voltage. Professor Fortescue has already described the excellent method of getting that high voltage by means of a valve, and I should like to add a few remarks to what he has said in that respect. If accurate measurements are to be made, and we have this high-voltage steady current applied to the tube, we want to get rid as much as possible of the ripples, and in order to do that it is necessary to use a high-frequency generator of 1,000 or 2,000 cycles per second; otherwise, if we only use a 50-cycle supply we shall find that our "smoothing-out" condensers and inductances are of undue size. On the other hand, if we use 2,000 cycles we can produce an almost uniform voltage. Having got a voltage that we can regulate between zero and, say, 150,000, the only other thing to do is to adjust the tube to pass the required current, and that will give us all the results we want for the present. I was rather surprised that the question of gaps was not touched on in the paper. Major Kaye has alluded to that point, and I will add a few further remarks to what he said. I should like to ask Dr. Morton whether the comparisons between the induction coil and the transformer have all been made at the same maximum voltage, because, if so, one cannot help thinking that the transformer and the rectifier give a larger quantity of X-rays than the coil. If we have the same maximum voltage, the rounded shape of the transformer wave gives us a longer time at or near that high voltage than the coil which gives us a peak potential. No doubt there is a lot at the lower part of the wave which is useless, but there is also a great deal more at the top part of the wave. Supposing these voltages are measured with a spark gap, do we get that comparison? It depends entirely on the type of spark gap used. As Major Kaye said, it is useless to use a point gap if we want a strict comparison. We want to use a sphere gap which has a very small time-lag. The voltage at which a pointed gap discharges depends upon the rate of rise of potential. If we have a low rate it will go over at a low voltage, and it does not give us a comparison of the maximum voltage in the two cases of coil and transformer. I am convinced that the sphere gap is what we want. Mr. Wright referred in his paper to the question of the shape of the wave. He said that we could obtain a more peaked wave by using a resistance in series with the transformer. I think he is right, and that that is the direction in which one should work. Major Phillips referred in his paper to a paper by Messrs. Barr, Beeton and Taylor published in the *Electrician* dealing with the question of changing the shape of alternator wave-forms. They injected into the wave a capacity or inductance in order to get what shape they wanted. It is quite probable it can be done in that way, but I think a great deal can be done by working the transformer at a very high magnetic density in the core and using a resistance in series with it. We can get a very high peak in that way. It often happens that in ordinary electrical engineering we have to avoid the very thing which it is necessary to obtain, either in wireless telegraphy or in medical work. When we test insulation by a transformer we always try to avoid having to regulate the current with a resistance in the primary circuit, because we get a high maximum which is difficult to measure on a voltmeter, but for our work I think that such a transformer, with a high density in the core, placed in oil and regulated with a resistance, would give us as good a result as the coil. There is one final word I want to say on the question of the measurement of peak voltage. There are methods by which it is possible to measure accurately the peak voltage, but they require considerable precaution to ensure accuracy. I refer to the use of a hot cathode high-vacuum valve—the type of which Professor Fortescue spoke. In doing some work during the war on magnetos, I used that method for voltages up to 15,000 or 16,000. A paper has been published by Messrs. Campbell and Paterson on the precautions necessary in using that method, which consists in putting the valve in series with an electrostatic voltmeter. When the voltage rises to the peak the charge goes through the valve to the voltmeter; when it falls the charge cannot go back. I found that a very reliable method of measuring the maximum, and if research is undertaken, that is the method which should be used, unless it is intended to use a continuous high voltage, which is certainly the more desirable.

Dr. E. A. Owen: We are dealing in the X-ray tube with two main factors, namely, the voltage and the current. The voltage on the tube determines the wave-length and the current determines the intensity of the radiation. Both these factors, in my opinion, are important in radiography. The form of the voltage curve given by an induction coil is similar to that represented diagrammatically in Dr. Morton's paper; there is one prominent peak followed by a series of smaller ones. It has been shown experimentally by Professor Taylor Jones that the X-rays are given out at the same time that the high peak is reached. No impression is obtained on the photographic plate corresponding to the smaller maxima of the voltage curve, so that this part of the curve does not serve any useful purpose in the production of radiation. In fact, the current passing through the tube during this time only serves to heat up the anti-cathode, and for this reason it should, if possible, be entirely suppressed. This is partly done in certain rectifying devices where a spark between two points or two spheres immediately follows the discharge through the tube. Dr. Morton suggests, in his paper, that the efficiency of an apparatus for the production of X-radiation should be measured by the radiological result obtained from a given number of milliampere-seconds on a pastille. This was done by Levy some time ago (see *Röntgen Journal*, January 1917), and it may be of interest to quote his results here. The intensity of the radiation emitted by a bulb was measured by the rate of change of colour of a pastille of barium platino-cyanide, and the current passing through the tube was read on a moving-coil milliammeter. There are objections to taking the indications of the milliammeter as a measure of the current through the tube, since the readings of

the milliammeter depend upon the current wave-form, and this is not the same for a coil as it is for a transformer. Levy found, with the coil outfit at his disposal, that the milliampere-minutes required to change the colour of a pastille to a given tint increased rapidly with increase of current through the tube, whereas, with the interruptless transformer the milliampere-minutes required to turn the pastille to the same tint was practically constant for all currents through the tube. The comparison was made with a Coolidge tube under definite conditions as to equivalent spark gap and distance of pastille from the anti-cathode of the tube. The curves showed that up to 3 milliamperes through the tube the coil was more efficient than the transformer, but for higher currents the latter was by far the more efficient. Some experiments carried out quite recently at the National Physical Laboratory on the measurement of X-ray intensity by means of barium platino-cyanide pastilles, corroborate Levy's results with the coil outfit. In this case a standard Coolidge tube with tungsten anti-cathode was excited by a Watson 16-inch induction coil, the current through the primary of which was interrupted by a Sanax mercury break. The following results were obtained with the Sabourand-Noiré pastille placed at 10·3 cm. from the anti-cathode. The figures in the table give the times of the B dose corresponding to certain values of equivalent spark gap (between point and plane) and current through the tube as measured by an ordinary milliammeter. The other conditions such as rate of interruption of primary current (about 88 interruptions per second), time of contact, etc., were kept constant.

Current	Spark Gap (between Point and Plane)				
	5 cm. (36 kv.)	8 cm. (51 kv.)	11 cm. (66 kv.)	15 cm. (86 kv.)	20 cm. (111 kv.)
Milliamperes	Minutes	Minutes	Minutes	Minutes	Minutes
1	36·0	13·0	9·1	5·5	3·4
2	22·8	9·2	7·6	3·5	2·0
3	18·7	8·0	4·5	2·9	1·5
4	16·6	7·5	3·9	2·5	1·3
5	15·3	7·1	3·5	2·4	1·2
6	14·4	6·9	3·3	2·2	1·1
8	13·3	6·6	3·0	2·1	1·0
10	12·7	6·4	2·9	2·0	0·9
12	12·3	6·2	2·8	1·9	—
14	12·1	6·1	2·6	1·8	—

The table shows the futility of increasing the current through the tube above a certain value. For instance, with a spark gap of 15 cm., when the current is increased from 4 ma. to 12 ma., the time of dose changes only from 2·5 minutes to 1·9 minutes, so that in this particular case when the current through the tube is trebled, the time of dose is only reduced by one-quarter of the time of dose with the smaller current. In the case of the transformer, however, under the same conditions we would find, according to the results already mentioned, that if 4 ma. through the tube require 2·5 minutes to change the colour of the pastille from tint A to tint B, then for 12 ma. it would require approximately 0·8 minute; that is the number of milliampere-minutes would be the same in each case. It has already been pointed out that the coil has an advantage over the transformer in that it has no moving part, and furthermore the wave-form of the coil discharge is very suitable for the production of X-rays. The accessory to the coil, namely the break, is, however, a source of trouble. I believe there is room for great improvement in this part of the coil outfit, and it is a point which should be attended to without delay if the coil is to hold the field with the transformer. Until quite recently there was no satisfactory theory to account for the performance of the induction coil, but lately a theory has been put forward by Taylor Jones from which deductions have been made which agree remarkably well with practical results. The application of this theory to practice should lead to important developments in coil design.

Dr. G. H. Orton: Dr. Morton, in his paper, says, "The cry of the radiographer was still for more milliamperes," and it seems to me that this cry has probably been one of the chief obstacles in the path of advancement. It must be evident to all who have studied the matter that the milliammeter is a very misleading instrument, and is really no reliable guide to the amount of useful radiation. We say a transformer is not so efficient as a coil because the 60 milliamperes from it are only equal to, say, 30 milliamperes from a coil, and so on. Is this correct? Why should we assume that the milliammeter reading on a transformer current indicates the same thing as that of a coil current? Speaking from practical experience, it is evident to me that it does not, but I will leave it to others to explain this. The maximum impulse from a coil is of extremely brief duration, much more so than that from a transformer—so brief in fact that the milliammeter as at present constructed is incapable of recording it. It would suggest that if the true current from a coil could be measured we should find that in proportion it is less efficient than the current from a transformer; the milliammeter in the case of a coil records probably less than half of the true current. Again, Dr. Morton assumes from his experiments that the curves from a transformer and from a coil are very different, but I am inclined to doubt that also. I would suggest that the curve in the case of the coil is of such brief duration that its characteristics cannot be properly gauged from what can be seen on a rotating mirror. It is an undoubted fact that a very hard tube is not good for radiography. What then is the use of the extra height of the coil curve, and at what point on this curve do we get the most useful radiation? Surely the peak is of value only when we are using a very hard tube, as is the case in radiotherapy. If then we are agreed that a hard tube is not required for radiography, why is the top of the transformer curve of less value? With regard to the extra heating effect of a transformer current, may not that be explained by the fact that in the case of the transformer there is a shorter period of rest, so to speak, between the curves? The explanation of the superiority of the coil over the transformer, Dr. Morton says, has puzzled many radiologists. I admit it is very difficult—I might say almost impossible

—to explain a superiority which probably does not exist, for I firmly believe that, if again we can only bring ourselves to disregard the milliammeter, or at any rate not assume that that instrument is recording the same thing when connected to a transformer circuit as when connected to a coil circuit, and judge by the effect, say, on a photographic plate, we shall find that this assumed superiority of the coil is non-existent. It is true that the potential of a coil capable of bridging 12 inches or more of air is enormous, but, when we connect this to a tube that does not require more than say, a 6-inch gap, does this total potential come into play, and are not the potential of a coil and the potential of a transformer operating a tube of similar spark gap practically the same? Does not the potential drop to the requirements of the tube? If not, what does happen? Why does not the current bridge the 12-inch or, say, even the 6-inch gap? In other words, is not the high-voltage impulse of a transformer sufficient for radiography, and is not the useful part of the coil wave somewhere between its highest and lowest points? In the case of therapy our arguments are quite different. There we require the most penetrating rays we can get, and no doubt the peak of the wave is the most useful part of it. Personally I do all my therapy with a coil, and radiography with a transformer, and it seems to me that that gives the most satisfactory results at the present time. The bulk of the transformers in this country will not stand the constant overloading necessary to obtain suitable rays for deep therapy—though I have no doubt they can be constructed if necessary—and it is more difficult to get a transformer repaired and replaced in a short time than a coil. Further, with the double installation, if one breaks down the other is available and the work is not arrested. Mr. Wright, in his paper, implies that radiologists do not know what they want. We do not pretend to know how what we want is to be manufactured, but I think we may say that for radiotherapy we require a machine that will give us a current of very high potential, capable of operating a tube having a 12- to 14-inch spark gap; furthermore, it must be able to stand such potential for long periods without breaking down, and the current must be sufficient to enable us to give a full dose through 4 to 5 mm. of aluminium in a reasonable time, say four to six minutes, or less. In the case of radiography such high potential is not necessary, but we want a machine that will enable us to obtain radiographs of the chest at a greater distance from the tube and in less time than is at present possible, and without an intensifying screen. In designing such a machine, I would suggest that the type of tube to be used must be taken into consideration. The current through a gas tube is dependent on the ionization of the gases in it by means of a high-voltage current, and therefore an initial inertia of very high potential is necessary to produce this ionization. In the case of the Coolidge tube this, of course, does not apply, and there is nothing gained by building up a coil of a higher potential than is actually required to operate the tube. What we want is sufficient potential and more current available at this potential.

Mr. W. E. Burnand: I think the difference in the results obtained from the X-ray tube, excited by means of a coil, and alternatively by a transformer, is very largely due to the great rise in useful rays from a tube as the input is increased. If we take it that the output of useful rays varies as the cube of the applied voltage, we are likely to be under rather than over as a first approximation. If those curves of potential shown on the screen are plotted out on that cube basis, it will be seen that the upper parts of the voltage curves are the only parts which matter as regards production of useful rays; the other chiefly heats up the tube. Major Phillips gives us some rather difficult figures to work to, if we are asked to supply transformers of 2,000,000 volts. I believe that 1,000,000-volt transformers have been made in the United States and have worked at such a pressure, though not for long. I have seen insulators described for one of them 10 ft. long. For 2 million volts they would have to be 30 ft. long. A 1-million volt transformer was described some time ago in the technical Press and, judging by its dimensions, it cost something above £10,000, and probably would weigh over 20 tons. So I think such transformers are out of the question for the time being. The most hopeful part of the business is, I think, provided by the demonstration, by the curves thrown on the screen of the very short duration for which this high voltage is required. It is evident that the amount of energy required in the tube is comparatively small. Although I think it is impossible with present-day materials to keep that high voltage for any considerable period of time on the transformer, we might develop an apparatus which would maintain it long enough to give the required impulse to the tube; I think 1/200th of a second would be long enough. The apparatus I would propose for that would be substantially a transformer, but with an air-gap in the magnetic circuit, and excited by a small direct current. By that means we could have a transformer of reasonable size, and we could pass, for instance, a direct current of about 500 watts for five seconds. That would be enough, and the energy represented would be mainly stored in the air-gap and could be discharged when the primary of the circuit is broken in 1/200th of a second; it would give us over 200 kw. for that short period of discharge, allowing liberally for all losses, and I think it would meet tube requirements for a long time. My object in bringing this forward is that I am constructing such an apparatus, and it will weigh about 2 tons. If any enthusiast would like to bring his tubes and test them when it is ready, I will risk the transformer. I have a variable air-gap, so that we can vary the intensity of the discharge as well as the quantity, and we can start at a low value, and increase it until one or the other gives out. A useful feature is that with a given air-gap and a given primary current there is always the same amount of energy stored in the system, and discharged when the primary circuit is broken.

Mr. F. J. Harlow: I think the first thing which should be taken into consideration in designing a generator for high-tension current is the X-ray tube. It is most important that we should decide definitely whether the gas or the hot-cathode type of tube is to be used, because there is a distinct difference in the characteristics of the two tubes and it is conceivable

that the machine employed to develop the high-tension current will have to be different in the two cases. I am convinced at any rate that little progress can be made in research by using the gas tube, as one cannot control the various factors independently; for research, the hot-cathode tube is indispensable in order that the conditions may be definitely fixed. Fig. D shows roughly the difference in the characteristic curves of the gas and hot-cathode tubes. Curve (*a*) shows the way in which the current changes with voltage in the case of the gas tube, except probably the lower part which shows the kind of thing we should get if there were some source of ionization in the tube. As the voltage rises the current attains a saturation value, and it is not until we get ionization by collision in the tube that the current rises. It is the last portion of the curve—the portion corresponding to ionization by collision—that we have to deal with in the gas type of X-ray tube. In the hot cathode tube, on the other hand, we have a curve of the type (*b*) or (*c*), the former

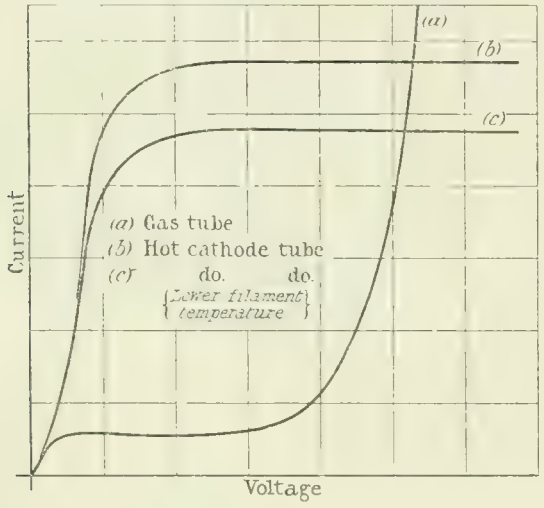

FIG. D.—Characteristic curves.

corresponding to the higher temperature of filament. For the low voltage, the current is quite small, but it attains a certain saturation value which depends upon the temperature. If the saturation stage is reached, however much the voltage is increased the current does not increase, a result quite different from that with a gas tube. It is thus conceivable that the most suitable wave-form may depend upon the type of tube used; at any rate, the characteristic curves must be borne in mind in interpreting any results such as those given by the oscilloscope. The paper which Dr. Morton has contributed describes the oscilloscope as indicating voltage; the oscilloscope indicates current approximately, not voltage, except in so far as the former is dependent upon the latter. The characteristic curves already shown reveal that the current is by no means proportional to the voltage. The next slide, Fig. E, shows the result of an oscilloscope experiment I carried out after reading Dr. Morton's paper; it illustrates the point extremely well. The experiment was performed with a high-tension transformer kindly lent me by Sir Archibald Reid, and I believe it is one of the first to be made in this country. A hot-cathode tube was used and for the lower voltages curves approximating more or less to the sine form were obtained. As the voltage gradually rises the indication of the oscilloscope follows the sequence of curves shown, until at a certain stage the top begins to flatten out, and however much the voltage is increased beyond this point the current does not rise further, but we get an absolutely flat top at a constant height, the curve broadening out until its sides become almost vertical. From the character of these curves and bearing in mind the shape of the characteristic of the hot cathode tube, one would think the dotted lines were voltage curves, but owing to the saturation stage having been reached they are not indicated in the oscilloscope. As a matter of fact, though I have not had time to take definite readings, it is quite obvious that if we plotted length of glow on the electrode of the oscilloscope against applied voltage

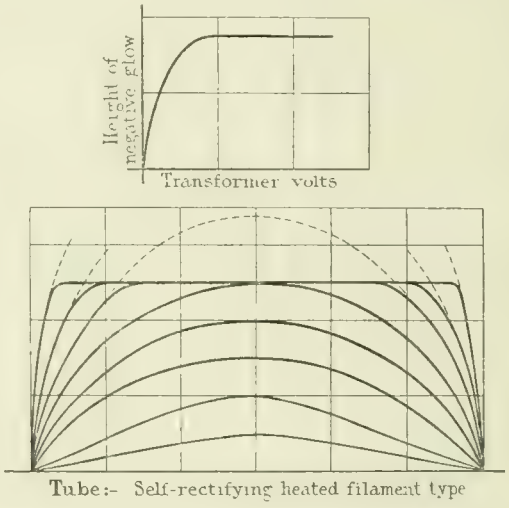

FIG. E.—Oscilloscope curves with high-tension transformer (without mechanical rectifier).

we should have obtained the second curve shown in this slide which is similar to the characteristic curve (*b*) of the first slide (Fig. D). Fig. F shows some oscilloscope indications with the instrument in series with a hot-cathode tube excited by a 16-inch coil. I want to show that the same sort of indication is obtained in this case. The first figure is for a low voltage. We get the initial peak which Dr. Morton makes so much of, but the curve quickly tails down to zero. If a spark gap is introduced into the secondary circuit the effect, as shown in the second figure, is to cut off the tail, which means, as Dr. Morton concludes, the cutting off of low-voltage current. It will be noticed that the number of milliamperes is reduced, although no alteration in the heating current was made. If the tube is hardened by increasing the primary current, it will be noticed [Fig. F (*c*)] that the curve assumes quite a different form, the maximum height being the same as before—viz. that corresponding to the saturation current. The height was in fact for the same heating current exactly that obtained with the high-tension transformer. The

effect of a gap in the secondary [Fig. F(*d*)] is much the same as before, but there is the same saturation current with, however, a slight initial peak, not visible with the gap absent. I think this is due to an accumu-

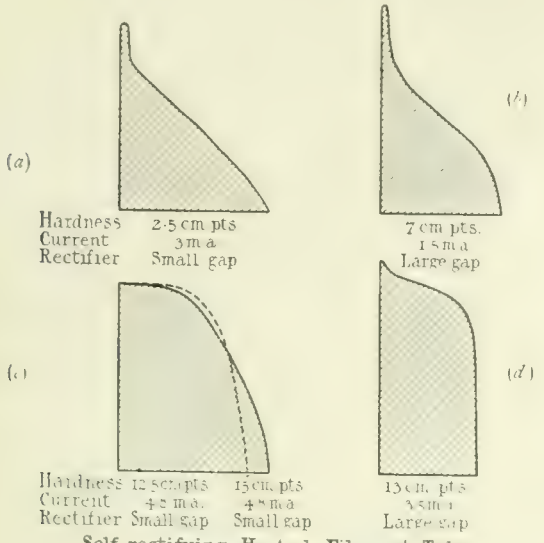

FIG. F.—Oscilloscope curves.

lation of electrons during the period of rest, and the more sudden application of the high voltage with the spark-gap in the secondary gives a higher current-density for a very short interval, after which it settles

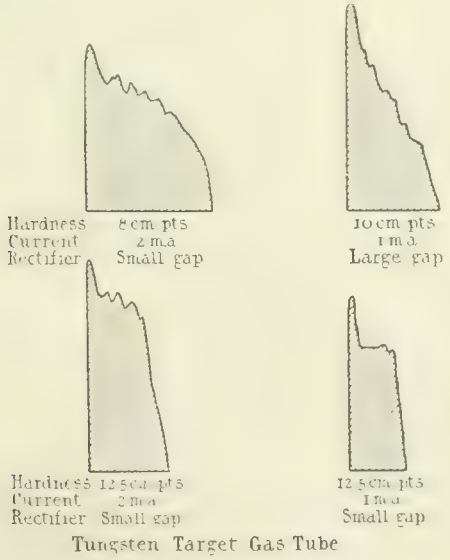

FIG. G.—Oscilloscope curves.

down to the saturation current until the voltage again falls below the saturation value. Fig. G shows a similar experiment with a gas tube, and it is seen that a different result altogether is obtained. There are oscillations taking place after the initial maximum has been reached, and the height of the curve is very different

for different conditions, a result which is to be expected from the nature of the characteristic curve. So, really, I do not think the oscilloscope can be taken to indicate voltage at all well; but the experiments I have made certainly agree with Dr. Morton's in showing that the effect of the spark-gap in the secondary circuit is to cut out the low-voltage current. I think the proper wave-form is one in which the voltage rises immediately to the high value corresponding to the requisite penetration of ray, remains there for the time it is required, and then returns to zero, so that we do not get any

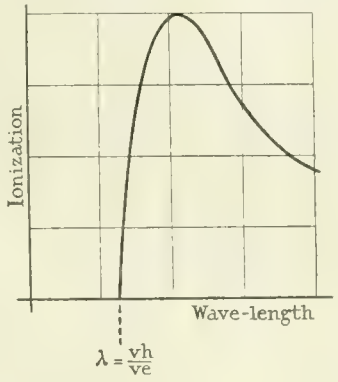

FIG. H.—Energy distribution in X-ray spectrum. (Duane and Hunt.)

of those low-voltage currents passing at all. It does not follow that there will be no soft radiation under these conditions, as seems to be supposed by many. Fig. H shows the form of the continuous X-ray spectrum obtained with a constant voltage of 40,000 applied to the X-ray tube. The curve is copied from a paper by Duane and Hunt. It will be noticed that

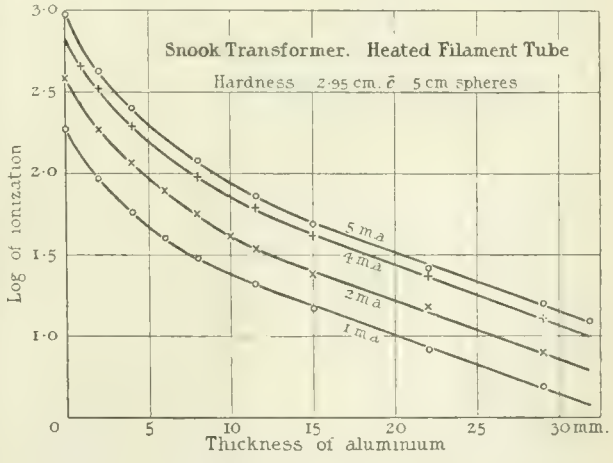

FIG. J.—Absorption curves; X-rays in aluminium. (E. J. Evans.)

ionization as a measure of intensity is plotted vertically against wave-length horizontally. Although we have a constant voltage applied to the tube, it does not follow that we are getting homogeneous rays; in fact we get a whole spectrum, and it is just the minimum wave-length of this spectrum which is related to the voltage

by the well-known quantum relationship. There is one other point of interest I should like to touch on, and I think it is important. Mr. E. J. Evans has carried out in my laboratory a series of experiments, the results of which are not yet published, but which he has kindly permitted me to mention. The quality of the X-radiation from tubes excited by different machines has been examined by absorption methods. Fig. J shows the type of result, which is not altogether new except that the curves have been obtained under more practical conditions than previously. Similar results have been obtained by Russ and by Rutherford. The logarithms of the intensities of the radiation getting through various thicknesses of aluminium are plotted, and it will be observed that after absorption through 10 or 12 mm. the curves become straight, which indicates that the transmitted radiation is sensibly homogeneous. It would therefore appear that after transmission

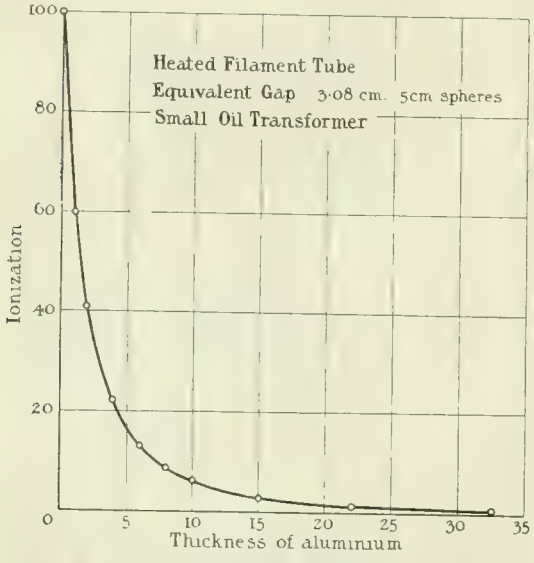

FIG. K.—Absorption curve; X-rays in aluminium. (E. J. Evans.)

through the human body, assuming the absence of secondary characteristic radiation, or through a thick filter, the X-rays approach homogeneity. I do not think this fact is sufficiently well realized by radiologists. The last slide, Fig. K, shows the type of absorption curve, the ordinates in this case being a measure of intensity, and it will be seen to what a large extent the radiation is cut down by 10 mm. of aluminium. In the example given in the slide, taken from results with the American army-pattern portable transformer, it amounts to as much as 94 per cent—i.e. only 6 per cent of the emitted radiation is transmitted through the aluminium. We have been trying to correlate the hardness of the homogeneous end radiation obtained from various machines with the voltage applied to the tube, but without success. For the same spark-gap different hardnesses of end radiation are obtained with different machines. We have used a coil, a Snook transformer, and an American portable transformer. Spheres of 5 cm. diameter have been used for measuring the equivalent spark-gap. It appears, therefore, that the spark-gap is not a proper indication of the hardness of the end radiation. However, if we take a different criterion, viz. the same hardness of end radiation for different machines, we find, on plotting out our absorption curves, that they are coincident within the limits of experimental error. It would therefore appear from this result—and we are hoping to investigate the matter more closely—that we get the same quality of radiation emitted from the tube by whichever type of machine we excite it, so long as the conditions are such that the same end radiation is produced. The surplus energy supplied, which is different apparently with the various machines, is absorbed in the tube, and we have the same radiation emitted. The difference in the amount of energy supplied is probably the low-voltage energy referred to earlier, which does not produce any useful X-rays. I think Mr. Evans's observations, if they prove ultimately to be correct, are extremely important, and will help to elucidate the problem of X-ray production. In conclusion, I should like to say that I think the future of the question under discussion to-night depends very largely on the physicist. I do not think we are really in a position yet to tell the engineer exactly what we want. I should like to make an appeal to the manufacturers of X-ray apparatus. I think if they would lend apparatus to physicists who are working in this direction a great advance could be made. The difficulty at present is that with our limited types of apparatus we are not able to vary the conditions of X-ray production sufficiently to enable us to ascertain in what direction improvements should be made.

Mr. H. M. Dowsett (*communicated*): The important fact which has been established is that the milliampere discharge from an induction coil is much more efficient for radiography than the same current from a transformer. Mr. Wright is inclined to blame the induction-coil ammeter for reading low, but there is no reason why this should be the case provided a hot-wire instrument is used with a period which is long compared with that of the coil interrupter, and it is constructed so that it is absolutely independent of frequency, instruments of this type being now easily obtainable. One advantage of the induction coil is that the highly damped discharge involves superposed current frequencies ranging from 500 cycles to 5,000 cycles and possibly higher, so that the initial current and potential rises are very steep and a minimum amount of energy is therefore wasted in heat before the potential applied to the tube reaches a value which is useful for radiography. The X-ray tube appears to be triggered by a fifth or ninth harmonic of the natural period of the coil secondary, while the working current is provided mainly by the fundamental and third harmonic. Another advantage is the interval between the discharges which enables the X-ray tube partly to de-ionize and also to cool. The result of this is that at the first moment of each discharge the electrons have an extra high speed, and as the temperature-rise is reduced the tube has a longer life. The interval is, however, needlessly long, particularly with large coils, and one object of design should be to lessen it. Before proceeding to offer some criticisms of suggestions put forward by

one or two speakers I should like to give my conception of how an induction coil works. A discussion of this subject should not be out of place here, and ought to be beneficial, particularly as no complete theory of the machine has yet been evolved, although the useful investigations of W. H. Wilson in 1912 and E. Taylor Jones in 1914 may be mentioned as having added to our general knowledge. My conclusions are based on the results of some recent tests which I have made on a Marconi 10-inch coil. The induction coil comprises three tightly-coupled oscillatory circuits: (1) The secondary circuit, which has a fixed period and is considerably damped, and comprises the secondary winding. (2) The primary circuit, which has an adjustable period and less damping than the secondary and comprises the primary winding and the coil condenser. (3) The interrupter circuit, which has an extremely short period and high damping, and comprises the interrupter condenser, the leads to the interrupter, and the interrupter itself across which a discharge takes place as long as the direct-current arc at the break continues. The secondary winding on open circuit oscillates as a coil with two free ends; the primary winding on spark load as a coil with one free end, that connected to the condenser; the interrupter circuit with one side of the condenser (that connected to the mains) practically earthed, while the other side makes a strong capacity coupling to the primary winding. Energy is first stored up in the form of a magnetic field which cuts both the primary and secondary windings by passing a direct current through the primary. It is then released by the stoppage, more or less complete, of the direct current owing to the opening of the interrupter contacts, and back electromotive forces induced simultaneously in both circuits cause in-phase currents which flow in one case into the interrupter condenser, and in the other into the self-capacity of the winding. If the coil is to produce the longest spark possible in the first oscillation, the whole of the magnetic field must be available to be taken up by the secondary winding. This means that the magnetic energy taken up by the primary must be given up again to the iron within the period of the first oscillation of secondary current so that it can feed this oscillation. Such an adjustment is obtained when the primary circuit has half the period of the secondary circuit. The primary oscillation then dies out, feeding the secondary oscillation, being also damped by the resistance leakage across the interrupter contacts, and if a suitable spark discharge takes place all the coil energy disappears. But if the discharge is not complete and current remains in the secondary winding, it forces an oscillation at its own period back on the primary, which results in a leading current, high potential on the interrupter condenser, and a knocking break. As the interrupter contacts open and the direct current falls, the back electromotive force produced by the falling magnetic field besides creating a rising condenser current also tends to maintain the direct current by an arc between the contacts. The sudden charge of the condenser, however, starts in the interrupter circuit a high-frequency current which is superposed on the arc, upsets its unidirectional character, and finally destroys it by its periodic oscillations through zero. I have not been able to trace any effect in the secondary circuit which can be said definitely to be due to the direct action of these high-frequency currents. Indirectly, of course, the more effectively the arc is quenched the more magnetic energy is available for transformation into secondary current. Given a properly adjusted coil the maximum secondary voltage, and therefore the spark length, is proportional to: (1) the magnetic field and therefore the primary ampere-turns; (2) the proportion of this field cut by the secondary, and therefore the coupling between the two windings; (3) the rate at which the field dies away, and therefore the natural frequency of the secondary circuit; (4) the inductance of the secondary winding; (5) the inverse of the decrement of the secondary circuit. The sudden method employed of starting oscillations in the two windings is a form of shock excitation, and therefore results in the oscillations being full of harmonics. When a spark is taken at less than the maximum the current is not given time to rise to its full value, and the oscillations show the frequency of the harmonic corresponding to the shortened period. Some values obtained from the Marconi 10-inch coil experimented with are:—

Secondary winding inductance, 470 henries.
" " self-capacity, 210 cm.
" " resistance, 6,650 ohms.
" " natural frequency, 480 $\sim$ per sec.
Critical damping resistance, $2 \cdot 84 \times 10^6$ ohms.
Coupling with primary circuit, 70 %.
Proportion of total field taken up by secondary on open circuit, 41 %.
Proportion of total field taken up by secondary on spark load, > 41 % and < 70 %.
Primary winding inductance, 0·0375 henry.
" " resistance, 0·2 ohm.
Capacity of interrupted condenser, 0·7 mfd.
Primary circuit natural frequency, 984 $\sim$ per sec.
Critical damping resistance, 462·6 ohms.
Frequency of primary circuit oscillations from oscillogram, about 500 $\sim$ per sec.
Interrupter circuit natural frequency, 265,300 $\sim$ per sec.
" " inductance, 0·5 micro-henry.
Critical damping resistance, 1·73 ohms.
Interrupter vibrations max. spark length, 45 per sec.

When sparking with 4-inch bulb X-ray tube on 2-inch point spark:—

Interrupter vibrations, 75 per sec.
Frequency of primary circuit oscillations from oscillogram, about 1,500 $\sim$ per sec.

Some hard and some soft 4-inch X-ray tubes were tested and found to have resistances when un-ionized from $1 \cdot 5 \times 10^{12}$ ohms down to 3×10^{10} ohms and, when glowing, resistances which ranged from 15×10^6 ohms down to $1 \cdot 5 \times 10^6$ ohms. The electrostatic capacity of such tubes is about 20 cm. It is clear from the above figures that if the spark discharge has a greater resistance than 3 megohms it will be entirely unidirectional; if it has a less resistance the discharge will be oscillatory, and in the case of some of the X-ray tubes tested each train should contain a few oscillations. But it must not be overlooked that as long as the

electrostatic capacity of the tube is small compared with the self-capacity of the coil, there will be an oscillatory current in the secondary winding independent of whether the discharge is oscillatory or not. The resistances of air-gaps and tubes becomes less as ionization proceeds, and the second and third secondary winding oscillations may under certain conditions be quite useful in providing additional energy for the discharge at a lower potential. It should now be clear why a smaller wire than No. 36 copper, as mentioned by Major Phillips, does not give better results in the average coil. The same length of wire will take up smaller space, so that both the self-capacity and the inductance will be greater and the resistance will also be greater. The period will therefore be slower, the maximum terminal potential difference and the secondary current will be less and the damping greater, and a larger condenser will be required across the interrupter. If aluminium wire is used which has the same gauge and insulation as the copper, the only constant altered will be the internal resistance. The maximum spark and secondary current will be less, and the heating in the winding will be greater, and the liability of the wire to break from ageing and mechanical shock will also be increased. The suggested use of oil for coil insulation would involve the use of a metal container. This would cause an increase in the capacity of the secondary winding, leading to a decrease in spark length, an increase in oscillation period, and, for best results, an increase in the capacity of the interrupter condenser. In comparing the induction coil with the high-tension transformer it is not fair to either to disregard the opposite principles by which they work. The induction coil is essentially a shock machine and gets rid of all its energy in the first kick of the current. The transformer either transmits the same amount of energy to the circuit every cycle, or else by the aid of resonance gradually works up the energy in the circuit to a maximum. An attempt to combine the two machines in one by injecting a condenser into the transformer circuit is likely to lead to the sacrifice of the best points of both of them. From the films shown by Dr. Morton the King's College single-flash coil appears to have a period quite comparable with that of the supply used for the high-tension transformer. As each discharge in a spark train on the coil film appears to grow and fade away gradually, the wave-form must be more sinusoidal and the oscillations less damped than is usual. This is to be expected from the size of the coil and its consequent high inductance. Finally, as regards the measurement of peak voltage, if the point gap is likely to give erratic readings, the sphere gap, due to its capacity, is likely to introduce an error. A gap between two spheres each 10 inches in diameter and 5 inches apart will break down at 200,000 volts (maximum), but the capacity of these spheres will be 273 cm., which is quite comparable with the self-capacity of a coil likely to provide such a spark and will therefore reduce the coil terminal potential difference. To avoid such error the sphere gap could be charged through a suitable battery of high-tension thermionic valves which pass no reverse current, using a similar circuit to the one employed by Messrs. Paterson and Campbell * for the measurement of magneto peak voltage, except that the sphere gap would replace the electrostatic voltmeter.

Mr. H. S. Holbrook (*communicated*): It is interesting to note that Dr. Morton and Major Phillips consider an induction coil preferable to a transformer, and that the reason suggested is the form of the secondary E.M.F. wave as shown in Fig. 1 of Dr. Morton's paper. If the penetration is proportional to the maximum value of the voltage it is easy to see that such a curve improves the penetration; but why should it give more actinism? It would be useful if comparative tests were made on some other wave-forms using, for example, a static influence machine or the new high-tension machine of Messrs. Evershed & Vignoles mentioned by Major Phillips. Has either of these authors ever obtained curves of the current through an X-ray tube by an oscillograph, cathode-ray tube or otherwise? These curves could help to explain the different heating of the tube when excited from a coil or from a transformer. The curves would not be the same shape as the voltage curves, seeing that an X-ray tube has not a constant fixed resistance throughout the voltage cycle. With a constant resistance the heating is proportional at every instant to the square of the current at that instant, and over a complete cycle of current the heating is proportional to the R.M.S. value of the current. This is usually a very different value from that shown by an ordinary milliammeter which measures the average value of the current. Has either of the authors used in his experiments an instrument giving R.M.S. values of the tube current, such as a thermo-ammeter? The wave-form shown in Fig. 2 of Dr. Morton's paper is typical of a single-phase transformer and a mechanical rectifier. I should like to ask Dr. Morton whether he has ever tried a three-phase transformer and a set of six kenotrons (hot-cathode valve tubes) or other suitable rectifier. Such an arrangement gives a wave-form with a variation of only 13 per cent from maximum to minimum, i.e. it varies from a maximum down to ·87 per cent of maximum value and then back again, unlike the single-phase arrangement which varies from a maximum to zero. In consequence the hardness of the X-rays from a tube excited from such a three-phase set would be very uniform, practically all the soft rays being eliminated. Moreover, for the same maximum voltage the three-phase transformer set would pass approximately 50 per cent more current through an X-ray tube than a single-phase transformer operating under the same conditions would do. Would not this be a great advantage in therapy and the radiography of metals and help to shorten exposures? I do not think there will be any difficulty in building transformers for any voltage that future developments may require. In the testing departments of cable makers and the big manufacturing companies there exist already many high-voltage transformers. For example, I have a photograph here of a single-phase transformer in the high-voltage laboratory of the General Electric Company of Schenectady, U.S.A. (makers of the Coolidge tube), which transformer is rated at 750,000 volts (R.M.S.) or for a peak voltage

* *Philosophical Magazine*, 1919, vol. 37, p. 301.

of over 1,000,000 volts. That transformer occupies a floor space of 13 ft. × 8 ft., is 15½ ft. high to the top of the tank, and 28 ft. over the terminals. These dimensions are large, but are necessary to prevent the disastrous "effluve" mentioned by Mr. Wright. I can assure him that the average purchaser of power transformers will not tolerate the least sign of effluve or corona. It is common practice to test the terminals of such testing transformers by applying 50 per cent over normal voltage in the dark. Of course the customer has to take the manufacturer's word that things are all right underneath the oil, but some customers call for the drawings and, choosing a part they think looks doubtful, pay for a full-size model of that part to be made and tested in a tank under oil, and again in the dark but with otherwise unimpeded vision, to see if they can detect the slightest sign of leakage. Another photograph which I have here shows a smaller transformer by the same company, rated at 300,000 volts (R.M.S.), and a further photograph shows an arc between terminals 43 inches apart. The arc was produced at an R.M.S. voltage of 362,000 or a peak of 510,000 volts, and was 25 ft. long. I gather that the milliammeter reading of the current through the X-ray tube is no certain measure of the quantity of X-rays produced. Some years ago I heard of an "intensimeter" using a selenium cell which was said to indicate quantity directly. Have the authors had any experience in the use of such an instrument?

Dr. R. Morton (*in reply, communicated*): In view of the discussion being only postponed and not yet ended, and considering the high probability of some very important matters being brought forward at the next meeting, comments made at this stage must be of a very tentative character as well as lacking in completeness. I think all will agree that the holding of this discussion has been more than fully justified. The co-operation of the members of the Institution of Electrical Engineers and the Röntgen Society, with their vast knowledge of physics and engineering, has carried the subject far beyond anything that could possibly be attained in any meeting of radiologists. It would, indeed, appear that the latter stand to gain the most; but with the rapidly growing recognition of the value of the X-rays for industrial and other non-medical investigations, I have more than a hope that it will be not so one-sided as this.

With regard to my paper, I wish to apologize for a certain looseness of expression and other inaccuracies, though probably none of them are very serious under the circumstances. Such errors are sure to crop up when a subject of this kind is tackled by one who is neither a physicist nor an electrical engineer. Mr. Clinker is quite correct in his criticism of Fig. 1 and also when referring to my use of the terms "voltage" and "current." These are of course very different, and yet they mean very much the same thing to the practical radiologist. With any normal tube of the gas type, with which we are perhaps most familiar, the resistance of the secondary circuit remains sensibly constant during any ordinary use for either diagnosis or treatment, and any variation of voltage is immediately accompanied by a corresponding variation of current. The Coolidge tube has altered all this and we must remember to be more careful in future.

Taking the discussion as a whole and in so far as it applies to the particular points raised in my paper, I have every reason to be content. It appears to be quite generally agreed that efficient radiation demands an extremely high electron velocity, and this depends on a correspondingly high voltage. The high efficiency of the coil as compared with the transformer, notwithstanding its smaller output, is due, as Mr. Dowsett points out, to its being a shock machine, getting rid of all its energy in the first kick of the current. There seems to be no doubt that, whatever be the means of generating current for the X-ray tube, the efficiency of the group will steadily increase the more the inflow partakes of the element of shock. If we could have a transformer of the Snook type that would give us, say, 1,000 impulses per second instead of the usual 100, or thereabouts, efficiency would rise enormously. A sine curve and radiation efficiency are not incompatible provided the periodicity be sufficiently high to give the necessary abrupt rise in voltage. The film of the single-flash coil illustrates this quite clearly. There is one point on which I have been partly misunderstood. Mr. Holbrook, for instance, states that I consider the coil preferable to the transformer; this is only partly true. I prefer the coil for some things—the transformer for others. The latter, if of large capacity, enables us to get results easily that are difficult or impossible to obtain with a coil, but it does so at the cost of an enormous waste of energy. I have tried to confine myself to the matter of the relative efficiencies of the two systems—not their possibilities—and we want if possible to turn all this wasted energy of the transformer into useful radiation. At present there is far too much low-voltage current producing useless radiation and heat that is very damaging to X-ray tubes. This is not so serious with a Coolidge tube, and the efficiency of the transformer is higher for obvious reasons; and for the same reasons, as Dr. Owen points out, this efficiency continues to rise with a rise of voltage and current at least up to a certain point. This observation brings to my mind a matter I have thought of at intervals for some years past, and one that seems to be worth considering at this juncture. Is it not possible that we have almost, if not quite, reached the limits of the X-ray tube as at present constructed? The power of the larger X-ray plants has increased enormously during the last 10 years or so, but there has been no corresponding radiological gain. This has been almost trifling by comparison.

In conclusion I wish to express my thanks for the kind attention accorded to my paper, and more particularly to those who have contributed to the discussion. Their observations and criticisms have been most helpful, and I am grateful to them, one and all. In saying this for myself I am also expressing what is in the minds of all my colleagues in the Electrotherapeutics Section of the Royal Society of Medicine.

Major C. E. S. Phillips (*in reply, communicated*): With regard to the references made during the discussion to some of the points raised in my paper, it

may be of interest, in connection with Professor Salomonson's valuable contribution, to point out that during the war, and at the suggestion of Mr. Brinkworth, a practically non-inductive resistance consisting of a stream of water flowing in glass tubes was set up for the comparison of output of various induction coils at the War Office X-Ray Laboratory.

The fact that a Coolidge tube does not emit X-radiation until the potential difference at its terminals reaches 10,000 volts appears to explain Mr. Clinker's result.

In reply to Mr. Burnand, I wish to point out that there is certainly much to be said against attempts to obtain the 2,000,000 volts by means of a transformer. The question is under consideration in several directions and a number of different schemes have been suggested already, none of them as far as I know involving the use of a transformer. I venture to predict that a practical solution will be found before long. It is necessary to realize that a special type of X-ray tube must also be evolved for use at this enormous pressure, or a modern tube made with increased length.

We must all be obliged to Mr. Dowsett for his attempt to simplify the complicated problem of induction coil design and for his explanation as to the best size of wire for the secondary. I advocated the use of aluminium in cases where the saving of every ounce of weight is of importance; even to the point of some loss of ray efficiency of the apparatus as a whole. I do not agree that if oil were used the container must be made of metal.

The aim of the "injector" method is to give a primary current curve exactly resembling that obtained with an induction coil. It is reasonable to expect that with a suitable secondary and an open magnetic circuit the same type of secondary discharge would be obtained as with a coil. That should give less heating of the tube and therefore increased ray efficiency without the limitation due to the use of interrupters.

In reply to Mr. Holbrook, I have no records of the current variation referred to. It is a difficult matter, but Professor T. Jones has suggested a method which I understand is being applied to the problem referred to. I have had some experience with selenium cells but always found that they showed deterioration with time. It is certainly desirable to make new attempts to produce a constant selenium cell, and I would suggest that its sensitiveness for X-ray work could be increased by enclosing it in a box coated upon its inner walls with some of the material used for modern intensifying screens, so that the action of the fluorescent light would add its effect upon the cell to that of the direct radiation.

Mr. R. S. Wright (*in reply, communicated*): I think the remarks of the various speakers thoroughly justify the statement I made, viz. that the whole subject is one about which we know very little. The general trend of opinion at present seems to be that on the whole the coil is best for therapy and the interrupterless machine for radiography, also that the wave-form is important with a gas tube but not to the same extent with a Coolidge tube. Exactly what wave-form is most desirable is not apparently quite so clear, and we are as far as ever from finding any really satisfactory means of reading the output in terms of efficient X-ray radiation.

The figures put forward by Major Kaye to the effect that the proportion of energy used to the final effective radiation is approximately 10,000 to 1 are probably within the mark, but the bulk of the loss is in the tube itself and not in the transformer, which Major Kaye estimates as having an efficiency of 90 per cent. In my opinion this figure is much too high, though I notice that Professor Salomonson practically corroborates it, but even if we put it at 70 per cent it is evident that the production of a wave-form which will give us a greater ratio of efficiency *in the tube* is more important than increasing the efficiency of the transformer.

Dr. Owen has contributed some valuable data which have an important bearing on the question of coil versus transformer. If his figures are correct they tend to show, for therapy at least, that a coil is of little use with big outputs, whereas with a transformer the effective radiation is pro rata to the current. Probably Dr. Owen's results will be criticized by others, and I do not imagine that he puts them forward as conclusive, but so far as they go they support the contention that a transformer is essentially an instrument for *heavy outputs*, while a coil is inherently suitable for producing rays of greater penetration but less intensity.

With regard to the question of insulation, I am duly grateful for the suggestions put forward. Professor Fortescue suggests that a careful study of the elementary laws of electric fields would solve the problem that I and others have been investigating for over 20 years. I wish that he would indicate to me how the desired result could be obtained, and, incidentally, the knowledge would be worth a small fortune.

Mr. Holbrook has criticized me even more, and assures me that in power transformers the effluve that we are trying hard to get rid of would not be tolerated. He has, however, gone further than Professor Fortescue and given us his solution, which is a transformer measuring 13 ft. × 8 ft. × 15½ ft. high and 28 ft. between the terminals. It is true that this transformer gives a higher voltage than we are at present looking for, but does Mr. Holbrook imagine that an instrument measuring a fraction of these dimensions would be "tolerated" in an average doctor's consulting room, or even that it could be got through the door?

Apparently Mr. Burnand is actually constructing a very similar apparatus which is to weigh 2 tons. If he will let me know when it is ready I shall be delighted to risk a tube or two in trying it.

Finally, with all due respect to Major Phillips, I must reiterate that the only real danger to insulation lies in the secondary windings, and if he is having trouble with condensers either the coils he is using are badly designed, i.e. without due regard to what Professor Fortescue calls the "elementary laws of electric fields," or the condensers themselves are of faulty construction.

DEFECTS IN ELECTRICITY METERS.

By Walter Lawson, Associate Member.

(*Paper received* 26 *March, and read before the* South Midland Centre, 14 *April*, 1920.)

This subject is important both by reason of its bearing on the cost of meter maintenance, and as affecting the correct registration of energy in generating stations and on consumers' premises. Nevertheless, only an insignificant amount of published information is available relating to this particular aspect of metering. Such treatises on electricity meters as can be obtained in this country deal exhaustively with the theory and design of all the well-known types, but make no reference to the relative reliability of the various instruments when working under service conditions. Possibly this is due to absence of the necessary statistics on which to base statements under this head.

The system of ascertaining, classifying and summarizing defects which I shall describe I adopted some 15 years ago, and since then altogether about 10,000 meters have come under review. The method is briefly this. Every meter removed from service is tested. If it is within the B.O.T. limits of error it is classified as a correct meter. If it is slow beyond the limits throughout its range, it is marked down as a slow meter. Similarly if it is fast throughout it is termed a fast meter. Meters which do not come within these three classes are mechanically defective, and the nature of their defects is ascertained in the Repairs Department. A meter may have several defects, but in the following table, in order to avoid complexity, each defective meter is classified under its dominant defect. The table represents a comparative summary of the off-circuit condition of a number of mercury motor meters of three different patterns, which are distinguished by the letters A, B, and C. A is now obsolete; B and C are of modern design. All the defects enumerated in each case were those which developed in the 12 months March 1913 to March 1914. Considering the much greater length of service of the old type meter, the modern meters could claim no superiority in point of reliability.

Condition when Removed	No. of Meters			Remarks
	A	B	C	
Correct	101	315	331	—
Fast	15	35	47	Average error 5 %
Slow	30	50	10	—
Armature peeling	6	49	100	Absent in later meters. Will not recur
Mercury oxidized	24	70	9	—
Armature clogged between poles	3	34*	76*	—
Armature-bearing jewel worn	6	9	16	—
Counter defective	17	24†	58†	—
Stopped by corrosion	7	25	—	—
Damaged by overload	6	7	1	—
Total No. of meters removed	215	618	657	—
Percentage defective	52·9	49·0	49·7	—

* Trouble largely eliminated.

† Mostly cyclometer counters; use discontinued.

The degeneration of the mercury motor meter with advancing years of service is illustrated by the figures given below. The meters under consideration in this case were all purchased in 1911. The percentage defective of total removed from service is given for 1912 and succeeding years.

The obvious conclusion which one arrives at from

	1912	1913	1914	1915	1916	1917	1918	1919
Percentage defective of meters removed	23·5	31·5	50	—	78·5	82	82	75

such figures as these is that in order to maintain the meters in service in good condition, they should be exchanged about every four years, whether suspected of being faulty or not. This was in fact our standard practice before the War, but during the War, owing to depletion of staff, it had to be dropped. The effect of this on the condition of the meters is strikingly indicated by comparing the statistics of " stopped " meters for the years 1914 and 1918.

Year	No. of Meters in Service	No. of Meters found Stopped	Percentage of Stopped Meters
1914	12,963	240	1·8
1918	14,607	468	3·2

Alternating-current Meters.

Alternating-current meters have a pronounced advantage over direct-current meters in that their defects usually are not of so serious an order. Stoppages are rare and, moreover, the majority of the defects that arise can be easily and quickly remedied. The subjoined table is interesting mainly as showing the various kinds of defects to which alternating-current meters are liable. The table deals with a heterogeneous collection

Low-tension A.C. Meters Removed from Service.

Condition of Meters after Testing	No. of Meters	Remarks
Correct	229	—
Fast..	97	Average error 4·5 %+
Abnormally fast ..	22	Average error 10 %+
Slow	23	Average error 4·5 %−
Jewel bad	76	Average error on 1/10th load = −10 %
Pivot broken ..	3	—
Pivot worn ..	1	—
Top pin broken ..	4	—
Dirty mechanism ..	59	Meters slow on low loads
Counter defective ..	14	—
Creeping on shunt..	114	—
Insulation faulty ..	1	—
Magnet touching rotor	12	—
Shunt coil shorted..	5	—
Total ..	660	—

of single-phase meters taken over from another undertaking when Birmingham extended its boundaries. The meters had been somewhat neglected and were generally in bad condition, hence the formidable array of defects revealed on removal. A study of these defects, however, does not lead one to conclude that in the mass their condition resulted in any serious loss of revenue to the undertaking, although individually many of them were extremely inaccurate.

My concluding table refers to 230 extra-high-tension three-phase meters taken off circuit during the past five years, and is indicative of the results that can be obtained by the use of a really high-class meter. These meters are employed in connection with large power supplies, and are the subject of the utmost care and attention, both as regards initial calibration and during the period of service.

E.H.T. Meters Removed from Service.

Condition when Removed	No. of Meters	Remarks
Correct	133	—
Fast..	Nil	—
Slow	5	Average error 2·9%−
Rotor bearing jewel worn	55	Average error on 1/10th load = −5 %
Dirt in top rotor bearing	34	Ditto = −3 %
Defective shunt coil	3	—
Total ..	230	—

The perfect ageing of the brake magnets employed in this meter is convincingly proved by the absence of any instance of a meter becoming fast. Apart from the defective shunt coils noted, the only troubles are with the wearing of the rotor-bearing jewel, and the tendency for dirt to collect in the pivot hole in which the top pivot of the rotor spindle is centred. The latter could very easily be remedied. The frictional errors thus introduced are of no account until the fifth year of service, when it is advisable to remove the meter for overhauling. The heavy casualties in the jewels is attributed to the unreliable nature of the sapphires, which vary considerably in hardness, and to the fact that in these meters the number of revolutions of the rotor may be anything from 3 to 7 millions per annum. This trouble could be reduced by using oil-immersed jewels, but the only satisfactory solution is in the adoption of the diamond-cupped jewel. Unfortunately, these are almost unobtainable at the present time. Meter users in this country will not, apparently, face the extra cost, and the prospective demand is too small to induce firms to put down plants for manufacturing diamonds in this form. One enterprising firm has indeed gone into the question and has estimated that the selling cost per jewel would be 17s. 6d. This is not a serious outlay with meters of large capacity, as for instance 195 extra-high-tension consumers' meters in Birmingham, which in the year 1919 integrated 56·5 millions of units, representing a sum of £326,574. Altogether, I have about 100 diamond jewels in use, and they have proved to be of immense benefit in station meters, on gener-

ating ring-main, and traction panels. Previously, some of these meters with heavy rotors had to have the jewels exchanged every three months, and were a source of constant complaint through erratic registration.

General Remarks.

The cost of repair is a serious item in the maintenance of meters to-day, particularly in the case of direct-current meters. There is room for, and great need of, improved designs of mercury motor meters, which will not only reduce defects but also simplify repairs. A meter designed to enable any defective part to be removed and replaced on the test bench would be of considerable advantage.

The prevalent impression that meters are an unreliable class of instrument is reflected in the timid guarantees laid down in the British Standards Specification. At the present time the price of a meter is no measure of its quality, and to protect buyers more rigorous guarantees against latent defects and impaired accuracy are needed. These improved guarantees might be made to apply to first-grade meters, whilst the existing clauses could suitably stand for second-grade meters.

This subject of meter defects is not of interest to engineers generally and, as a direct consequence, rarely comes under discussion. In view of this, it is to be deplored that meter engineers themselves do not come together to compare methods, discuss difficulties, and exchange information. Such co-operation could not fail to bring to light a vast amount of knowledge which would be of mutual assistance not only to themselves, but also to those engaged in the manufacture of meters.

Discussion before The South Midland Centre, at Birmingham, 14 April, 1920.

Mr. A. T. Bartlett: The statistics which the author gives are interesting and important, but their value would be greatly increased if similar figures were forthcoming concerning other meters. From these tables it seems that a large percentage of the failures are due to faulty jewels, and in this connection I should like to ask whether any attempt has been made to substitute harder metals such as tantalum and tungsten. Sir William Crookes at the meeting of the British Association held some years ago in South Africa exhibited a piece of tantalum against which a diamond had been rotated, if I remember rightly, several million times and the diamond had suffered as much as the metal. Such a "jewel" would probably be cheaper than a diamond.

Mr. A. T. Thurman: Among the mechanical defects of mercury motor meters is the common one in ampere-hour meters used for registering the discharge of batteries, of the small pawl sticking and letting the meter run backwards when the current is reversed whilst the battery is on charge. This is a serious fault, especially when the battery is used for balancing, as the battery may in time be damaged through an incorrect record of its discharge. The table showing the condition of 230 extra-high-tension three-phase meters removed from service speaks well for this class of meter, but the accuracy of these meters as shown on the test bench is not a true indication of their accuracy when in service, since the accuracy of the instrument transformers with which they work is an important factor, especially the ratio of the current transformers, which should be tested with the meters if possible. I have known cases where meters which have been passed from the test bench as correct and which on being tested with a check meter in service have appeared to be reading correctly, were afterwards found to be reading inaccurately owing to a faulty current transformer.

Mr. A. Howell: Engineers connected with the meter departments of electric supply undertakings have experienced considerable trouble with the armatures of mercury motor meters. For some years the principal method adopted for insulating all but the conducting edge of such armatures was by means of fabric coatings treated overall with an enamel, and later by using a special enamel or varnish alone. Unfortunately, after a year or two's service such coverings began to peel away, allowing the mercury to get underneath, amalgamating the disc in patches and thus causing a change in the behaviour of the instrument, with ultimate failure from clogging of the mercury bath. In the author's tables types B and C show a large proportion of such defects. It would appear that recently makers of such meters have in many instances abandoned the idea of insulating the major surface of the armature disc, adopting simply a clean amalgamated surface, without causing any marked difference as to accuracy. Taking the various types of meters as a whole, it is interesting to note that quite a large percentage of failures is due to jewel troubles, perhaps not so pronounced as regards the mercury motor meter as with the purely motor type. Considering the great weight of rotor or element placed upon the little jewel in many makes of such meters, I am not surprised to hear that considerable trouble is still being met with in this direction. Will the author give us a little more information on the point?

Mr. W. Lawson (*in reply*): In reply to Mr. Bartlett, the absence of any mention of certain well-known types is a deficiency which I found impossible to meet within the limits prescribed for this paper. Doubtless in his reference to "other types" he had in mind electrolytic and commutator ampere-hour meters. Defects in electrolytic meters are not so numerous as in the mercury motor type, and in the one which has water for its electrolyte they are almost negligibly few and those that do arise are due to special causes such as overloading. In the case of the type in which mercury is precipitated, the percentage of yearly removals due to defects is about half that of the mercury motor meter: moreover, the figures for successive years indicate less deterioration with increasing years of service. Commutator ampere-hour meters show a considerably higher percentage of defects than any other type. The slightest tarnishing of the commutator or brush contacts affects registration and frequently

leads to complete stoppage, and it is to this cause that the greater proportion of the defects owe their origin. In districts where atmospheric conditions are not detrimental a much lower percentage of defects might be expected. I consider Mr. Bartlett's suggestion as to the possibility of making use of the harder metals for the rotor bearings of meters to be one of great value. I know of no attempt having been made in this direction and it is to be hoped that manufacturers will not be averse to taking the hint. Undoubtedly here is a useful field for research which may lead to the solution of the jewel problem.

I agree with Mr. Thurman as to the seriousness of the trouble caused by the frequent sticking of the pawl in battery ampere-hour meters. Extreme liability to mechanical failure in an essential detail cannot be too severely condemned, and especially does this apply to an instrument upon the records of which so much depends. Inherently faulty design is answerable in this case. The remedy is to reduce friction to a minimum by supporting the pawl pivots between jewelled centres. With regard to the tests on the 230 extra-high-tension meters, these were in each case carried out with the meter connected to the same current transformers by which it was operated in service. The practice of testing such meters separately from their current transformers has, I believe, been generally discarded.

In reply to Mr. Howell, the peeling off of the enamel or varnish coatings of the armatures of mercury-motor meters was at one time a grave trouble; happily it is now a thing of the past. Makers who still retain the coated armature have, by perfecting the process of protection, rendered a recurrence of the trouble improbable. The simpler method of using a bare armature, although regarded by some users with a certain amount of suspicion, is a sound one. My own experience extending over eight years has revealed no objectionable result from the employment of bare armatures. The jewel troubles of mercury-motor meters are actually as numerous as in the heavier rotor types. In the tables referred to, only the dominant defects are numerated; in many instances jewel defects are masked by defects of a more serious order. The magnitude of the jewel troubles in mercury motor meters is remarkable, in view of the fact that the pressure exerted by the armature pivot on the jewel does not exceed the weight of one gramme. It is a phenomenon that awaits explanation and the remedy.

THE PROTECTION OF ALTERNATING-CURRENT CIRCUITS AND APPARATUS.

By E. T. Norris, Student.

(*Abstract of paper read before the* North-Western Students' Section, *at* Manchester, 9 *December*, 1919, *and before the* Students' Section *of the* Liverpool Sub-Centre, 9 *January*, 1920.)

Synopsis.

The importance of protection in present-day power-supply systems; general requirements of a protective system; operating principles; classification of systems; ideal characteristics; types of faults.

Protection of transmission lines and feeders; independent and parallel feeders; interconnectors; reverse-power relays; Merz-Price, split-conductor, core-balancing, protective sheath and other systems; considerations affecting choice of system.

Protection of apparatus; generators, transformers, switchgear and busbars; core-balancing, self-balancing, Merz-Price and other systems; comparison of individual methods.

Relays; instantaneous, time-element, reverse-power. Transformers; general considerations; special types.

Conclusion; effect of operating and local conditions on choice of protective system; value of suitable protective gear in economizing plant and mains; allowance for future extensions and alterations.

Introduction.

Electricity as a medium of power distribution presents two features of special interest from the protective point of view. There is no means of storing it in large quantities commercially and, as there is practically no flexibility in the transmission, trouble at the output end must inevitably affect the input. Therefore, to meet the first objection, the system must be arranged so that it is impossible for the whole of the generating plant to be shut down from any one cause of trouble, and, to overcome the inflexibility of transmission, any area of trouble must be removed from the system as quickly as possible.

In the early days of supply systems the circuits were very simple, consisting of individual cables from the generating station to each substation, so that any trouble that occurred could only affect the generating station and the particular substation on that route. Hence the only requirement of a protective system was to minimize damage to cable and machinery. With the growth of the supply system, the complication of circuits and the interconnection of substations, however, conditions have changed and a fault anywhere on the system can directly affect neighbouring parts. It thus became imperative to remove faults as quickly as possible in order to prevent disturbance to other parts of the

system, quite apart from the question of injury to the faulty circuit or apparatus. This aspect was brought into further prominence by the growing importance of continuity of supply. Modern industrial life, with its high degree of organization and rapid production, demands that its supply of power shall be absolutely reliable, continuous and unvarying. The result is that at the present time the function of protective gear in ensuring continuity of supply is of far greater importance than the mere protection of apparatus from damage.

Functions of Protective Systems.

The whole subject of protection may be divided into two branches :—

(*a*) Protection of material from damage.
(*b*) Preservation of continuity of supply.

Considering the consumer's point of view, faults and breakdowns of the supply system only affect him in so far as they interrupt his supply of power. There is no system of protection which will absolutely prevent faults from occurring. The most that can be done in the way of protection from damage is to confine the trouble to as small an area as possible and to isolate the affected part while the fault is in an incipient stage. The requirements of continuity of supply are, good and reliable machinery and apparatus, two or more sources of power to each substation (so that a single fault will not cause a complete shut-down) and, as in the previous case, localization of trouble.

A system of protective gear should, of course, operate whenever there is trouble in the particular section it covers, but, conversely, it should not operate unless there *is* trouble, and this latter characteristic is in many cases by far the more difficult to obtain. It is usually much easier to confine the trouble to a small area than to confine the portion of the system disconnected to an area correspondingly small. From the point of view of continuity of supply it is just as bad for a protective gear to shut down good apparatus or circuits as to fail to shut down faulty ones. This property of a protective system of being able to discriminate between good and faulty conditions is known as its selectivity or discriminative property.

Operating Principles.

When a fault of any sort occurs, whether on circuits or apparatus, the function of the protective gear is to disconnect the portion affected from the rest of the system, and it does this by operating the switches controlling that portion. The most reliable indicator of trouble in any electrical circuit or apparatus is the value of the current in it. Hence, without exception, all protective systems are current-operated, i.e. they depend for their action on the current in the circuit they control being abnormal either in magnitude or in phase. There are three ways of determining this abnormality and they depend on the basis of comparison :

(*a*) Abnormality compared with a definite fixed value ;
(*b*) Abnormality compared with the value in some other part of the circuit or apparatus ;
(*c*) Abnormality of path.

The whole field of protective systems can in this way be broadly divided into three classes, as follows :—

Class A.—Comprising fuses, overload devices, etc., where the operation depends on an absolute value of current.

Class B.—Comprising Merz-Price, split conductor, etc., in which operation occurs with a relative value of current.

Class C.—Comprising core-balancing, leakage devices, etc., which operate when the current strays from its proper path.

Abnormality of current shows that there is a fault somewhere, but it does not in itself indicate where the trouble is. Thus Fig. 1 shows a generating station supplying three substations in series. If a fault occurs at P there will be a heavy current in the line from A to P so that protective gear of Class A (or of Class C as will be shown later) would operate on all sections from A to D, and the sections A B and B C with the substations B and C would be disconnected although in quite good condition. Hence this type of protection gives no discrimination between the faulty section C D and the sound ones from A to C. The diagram shows

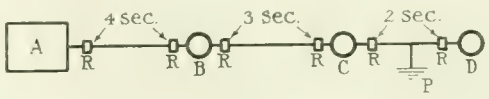

Fig. 1.

that the abnormal current extends from A to P, but that beyond P the current is quite normal. The current conditions in the line on either side of the fault are therefore different. This is important as it is the fundamental principle on which fault localization is affected. If each feeder were equipped with protective gear which only operated when the currents at either end of a feeder were different, no matter whether the currents themselves were normal or abnormal, i.e. protective gear of the Class B type, then only the section C D would be disconnected and the gear would be discriminative. It is seen therefore that protective gear of Classes A and C are not inherently discriminative though they will protect against damage. They can, however, be made discriminative to a great extent if conditions are not too complex, as will be shown later.

Practical Application

There are one or two portions of the protective circuit which are the same for all classes of gear, and it will simplify matters to study these properties first. Practically all systems of protection can have their connections divided into three portions :—

(*a*) The primary or high-tension circuit.
(*b*) The secondary or relay circuit.
(*c*) The tripping circuit.

The primary circuit forms the detector and records the actual electrical conditions in the apparatus or circuit concerned. As all protective gear is current-operated this circuit usually consists of the primaries of one or more current transformers. All variations

of the current are thus transferred to the secondary or relay circuit. This circuit is widely different in the various systems, but in all of them one or more relays are incorporated. These relays are energized when the gear is required to operate, and the operation of the relays completes the tripping circuit, the relaying contacts being connected in series with this circuit. The tripping circuit includes the trip coil on the circuit breaker and the power required to operate it. Fig. 2 shows these three circuits. In a few cases the trip coils themselves are connected in the secondary circuit, so that relays are not required. In general the primary and tripping circuits are the same for all systems of protection, the individual characteristics being in the relay or secondary circuit. In describing the various

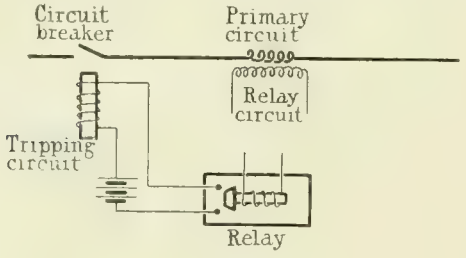

Fig. 2.

systems the tripping circuit will in general be omitted and only the two relay contacts shown.

Independent Feeders.

In the simple case of an independent feeder, protection is very simple. A fault of any sort, whether of the feeder itself or of the machinery in the substation, means the total stoppage of supply, so there is no need for discrimination, and overload protection alone would be sufficient. Where there are several substations in series, some discrimination is required, as explained in connection with Fig. 1, to prevent a fault on a distant section from shutting down all the intermediate substations. The systems of protection suitable are the following.

Overload time-limit.—Ordinary time-element overload relays are installed at the end of each feeder as shown in Fig. 1. The time setting is lowest for the most remote section C D and is successively increased for the nearer sections A to C. Thus if a fault occur at P the circuit breaker at C will operate within 2 seconds and the faulty section will be disconnected. The sections nearer the generating station will not be affected, because the fault is cleared before their time-limits are up. There must be sufficient interval between the settings to allow the circuit breakers completely to open the circuit. This interval, including the time required to operate the relay, varies from $\frac{1}{4}$ to $\frac{1}{3}$ second. This method is simple and cheap, but it requires a large fault current to operate it or it would trip out on ordinary overload. Moreover, the heaviest faults are most likely to be those nearest the generating station and these remain on the system for the longest time.

Core-balancing system.—In any three-phase circuit the sum of the currents in the three lines at any instant is zero under proper conditions. If, however, an earth occur on one line some of the current in the faulty line will return through the earth to the neutral point and the sum of the currents will no longer be zero. Hence, if a circular iron core be slipped over the cable there will normally be no flux induced in it, but when an earth fault occurs the resultant current in the three lines will magnetize the core. By placing a secondary winding on this core and connecting directly to a relay the feeder will be disconnected. This is the principle of the core-balancing system, which is simple, inexpensive and very sensitive. It will operate on a fault current of a few amperes, and time-element relays may be used to give selectivity as previously described.

Although this method gives very sensitive protection against earth faults, overload relays are still necessary to cover faults between phases and excessive overloads. The principal advantage of the sensitivity of this system is that a much larger resistance in the neutral may be used, so as to keep down fault currents to a safe value.

Protective-sheath systems.—Several methods of protecting feeders have been proposed, in which the conductors are enclosed in one or more metallic sheaths running the whole length of the feeder and insulated both from the conductors and from earth. In one such arrangement there are two sheaths, one arranged between the conductors and one surrounding them, in such a way that one or other of the sheaths must be involved whatever the nature of the fault. Normally there is no difference of potential between the sheaths, but each sheath is at a potential higher than earth potential, so that if either becomes earthed a current will flow and operate the gear.

Another system, introduced by Mr. C. J. Beaver, employs core-balancing transformers at each end of the feeder, with their tripping circuits interlocked through a sheath surrounding the cables. The relay connections are such that this sheath must be earthed before the gear can operate, in addition to the necessary unbalance required to operate the core-balancing relays. This prevents a healthy feeder from being shut down through feeding into a faulty section. All sheath methods involve special cables in addition to relays and transformers and, so far, this class of gear has not been extensively used.

Parallel Feeders.

The protection of parallel feeders is more complicated than that of independent feeders because of the necessity for distinguishing between the faulty and sound cables in the event of a fault on one of them. For faults at the near end of the line the current in the faulty feeder will be much heavier than in the sound one, so that time-element overload relays would be satisfactory. If a fault occurs at the remote end, however, the fault current will divide equally between the two feeders. In this case the infallible criterion of the faulty cable is the reversal of power at the receiving end. Complete protection will be given by a combination of reverse-power relays and overload time-limit relays interlocked to prevent operation on heavy external overloads.

The success of this type of protection depends on the reliability of reverse-power relays, and it was owing

to the unreliability of these that the method fell into disfavour for some years. Reverse-power relays have been greatly improved in recent years, however, and in America especially this system is widely used.

Merz-Price.—The idea of interlocking relays so that they are only operated by relative values of current introduces protection of the Class B type, often known as "balanced protection." The first of this class to come into commercial use was the well-known Merz-Price system. The principle is very simple and consists of relays at each end of the feeder interlocked so that the gear will only operate when the current entering the feeder at one end is different from the current leaving at the other. A transformer is installed at each end of the line and the secondary windings are connected together by means of pilot wires so as to oppose one another. Under normal conditions the pressures across the transformers will be the same, and as they are in opposition no current will flow. If a fault occur the current in the line at one end will be different from that at the other end, the difference being the fault current. The pressures in the secondaries of the two transformers will therefore be unequal, and the difference will force a current through the pilot wires and relays connected in series and so disconnect the feeder. The system gives complete protection for all kinds of fault and, compared with the systems previously described, is very sensitive.

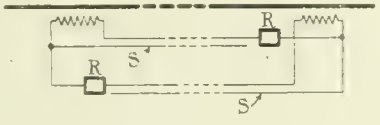

FIG. 3.

As a general rule a fault current equal to 50 per cent of full-load current is required to operate under the worst conditions, as compared with two or three times full load for the previous cases. The necessity for pilot wires is a disadvantage, and the transformers require careful attention. Their secondary voltages must be equal, not only in magnitude, but also in phase displacement and wave-form, for all loads right up to the heavy momentary overloads that may occur due to short-circuits in other parts of the system.

Another difficulty experienced, especially on long feeders, is caused by capacity currents in the pilot wires. With heavy primary currents, and the correspondingly increased secondary voltages, the pilot wires will have a considerable difference of potential between them. Capacity currents will be set up which, completing the circuit through the relays and transformers, may cut out the feeder although in sound condition. This defect considerably limited the application of Merz-Price gear for feeder protection. An ingenious arrangement has, however, recently been introduced and patented by Mr. J. R. Beard, whereby all capacity troubles are completely eliminated. Each pilot wire is surrounded by an insulated sheath (S) connected as shown in Fig. 3. All capacity currents are intercepted by the sheath and will flow through the transformer without passing through the relay. Not only does this eliminate the effect of capacity currents but it considerably simplifies the design of the transformers.

Split conductors.—In considering the protection of parallel feeders it was shown that the principal difficulty was to discriminate between the sound and faulty feeders in the event of a fault on one of them. By combining the two feeders and considering them as one unit this difficulty is eliminated. Each conductor is divided into two halves or splits insulated from one another. These two halves are taken in opposite directions through a transformer at each end of the line. The secondary winding is connected directly to the relay controlling the tripping circuit. Under normal conditions, the currents in the splits are equal, and will neutralize one another in the transformer, and the secondary will not be energized. A fault occurring on one split will upset this equilibrium and the difference between the currents in the two halves will energize the transformer and operate the gear. A fault occurring on both splits simultaneously might not destroy the balance sufficiently for the gear to operate, but this is very unlikely to occur on overhead lines, and on cables the possibility is rendered remote by arranging the splits concentrically or diametrically.

The system is extremely sensitive—a fault current of from 20 to 40 amperes being quite sufficient to operate the tripping circuit. The two splits must be of equal reactance and resistance and the two halves of the transformer primary winding must also be balanced. As in the case of parallel feeders, protection is complicated for faults at the remote end of the feeder. In this case the fault current will divide equally between the two splits, and the gear will not operate. There are two methods in common use for overcoming this difficulty. One is to bring the splits right up to the oil switch and have an additional contact so that when the switch opens it also separates the two splits and throws the whole of the fault current on to the faulty half.

The other method is to use transformers with a large reactance, or even to add external reactance. With the currents balanced the extra reactance would have no effect, but when a fault occurs the current will be in the same direction in the two halves of one transformer, resulting in considerable impedance. This path will then have considerably more impedance than the path through the other split, resulting in unbalanced currents and operation of the gear.

The relative merits of the two methods, split-contact switch or high-reactance transformer, are debatable. The tendency in England inclines towards the former, and in America towards the latter. For large currents the high-reactance method is probably the best, as the additional contact on large oil switches is not desirable. There is not much to choose either way on the score of expense. High-reactance transformers are considerably larger than the ordinary type, so that this is often the deciding factor in the choice.

INTERCONNECTORS.

These include all feeders in a ring main except those directly from the generating station. An interconnector can therefore never be the sole source of supply to any

point. It must nevertheless be securely protected, as the loss of one will cause some other part of the network to be overloaded and may leave it without a standby supply. The problem for a plain ring main can be solved by time-element and overload relays with suitably graduated time-settings. The general solution, however, is one of the balanced systems, either Merz-Price or split conductor.

Protection of Apparatus.

The principal items under this heading are generators and transformers. The considerations involved in the choice of protective gear are widely different for the two cases and they will therefore be dealt with separately.

Generators.—Complete protection of generators covers the usual type of faults as in the case of feeders, and, in addition, loss of field and failure of prime mover. For faults across different parts of the same phase there is no known method of protection, but fortunately they are very rare, the majority of faults being to earth. For this reason the core-balancing system is frequently used. For apparatus protection the connections are modified by including the neutral in the transformer

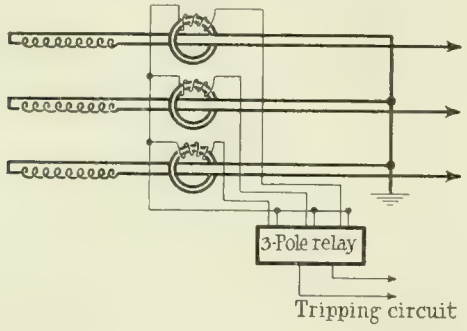

Fig. 4.

circuit. The gear can then only be operated by earth faults on the generator side and is unaffected by faults on the line side. It is thus discriminating and has all the characteristic advantages and disadvantages of the core-balancing system as previously described.

Reverse-power relays combined with time-element overload relays were extensively used at one time. Reverse-power relays are still used to protect against failure of prime mover and loss of field. Both these faults mean such a fall in generator voltage that the busbars will feed back into the generator.

Of the balanced systems, the Merz-Price is the one most commonly used. The principle, in a modified form, is the same as for feeder protection. The two transformers are connected in series instead of in opposition and the relay is connected across the equipotential points in the pilot wires. This system is called the "balanced" or "circulating current" system, to distinguish it from the form used in feeder protection or the "balanced voltage" system. The "balanced current" system is the more suitable for apparatus protection as it is easier to balance and is more sensitive. Under suitable conditions fault settings of 10 per cent of full load may be obtained. The balancing difficulty is still a drawback to this type of gear. All six leads of three-phase generators must be brought out and three transformers connected in the neutral. By mounting the other three transformers in the cubicles the leads from generator to cubicle are included in the protection. Moreover, as the pilot wires carry currents proportional to the load, overload protection can be obtained by inserting fuses in them.

Another form of balanced protection recently introduced and patented by Mr. J. R. Beard is known as the "self-balancing" system. The ends of each phase winding are taken through a transformer so that the currents are in opposition. A secondary winding on the transformer is connected directly to the relay. The principle is in fact similar to that of the "split conductor" system. Fig. 4 shows the system applied to a three-phase generator. The currents are directly balanced against each other, without the interruption of magnetic circuits. The system is therefore very sensitive and can readily be made to operate with from 20 to 30 amperes fault current. The generator leads cannot, however, be included in the protection without special sheathed cables. The greatest problem in generator protection is that of dealing satisfactorily with faults near the neutral point where the voltage is very low. The great sensitivity of the "self-balancing" scheme is an important advantage in this respect.

Transformers.—The same general principles apply for transformer as for generator protection. For isolated and individual cases the core-balancing system will meet the requirements. The great handicap of this type of protection in only taking care of earth faults is of more importance in considering transformer protection. In the case of generators where the windings are embedded in slots and surrounded by iron it is true that the majority of troubles will be faults to earth, and faults between phases will probably develop into faults to earth almost immediately. In transformers, however, faults between phases are quite common, whilst faults across different parts of the same phase, i.e. breakdowns between turns, are perhaps the most frequent of all transformer troubles. These are, in many cases, not likely to develop into faults to earth until the transformer is practically destroyed. It will be apparent therefore that core balancing cannot be considered a method of protection as efficient for transformers as for generators.

The Merz-Price "circulating-current" system is the one by far the most frequently used. The connections are the same as for generator protection, but there are several points and peculiarities in applying this system to transformers which do not arise in the protection of generators. There will be permanent unbalancing due to primary magnetizing current, ratio and phase-angle error, especially where the high- and low-tension protective transformers are of different types. The relay setting has therefore to be increased to cover this out-of-balance.

One of the most frequent faults in transformers is breakdown between turns, i.e. across different parts of the same winding. If this occurs in the primary a heavy current will flow which will not be reproduced in

the secondary. The gear will therefore operate. As this kind of fault is confined almost entirely to the high-tension windings, it follows that Merz-Price gear will give protection against breakdown between turns on step-down transformers. This characteristic gives this type of protection a marked superiority over all others so far as transformer protection is concerned.

Many of the disadvantages of the Merz-Price system are overcome in the "self-balancing" system. The principle is the same as for generator protection. Both ends of each phase winding must be brought out and the primary and secondary are treated quite independently. The ratio of transformation does not affect the protection, so that tappings cause no complications or loss of sensitivity. The system is also inherently proof against troubles due to rush of magnetizing current on switching in. On account of the simplicity of its connections, it is peculiarly suitable for the protection of Scott-connected transformers, and for all cases involving phase relationships, frequency variations and voltage differences. The disadvantages are very much the same as in generator protection. Due to the freedom from balancing, this system is extremely sensitive at all loads, the usual fault current-setting being about 30 amperes. As operation depends on the difference of current in the two primaries, the fault current-setting is practically independent of the k.v.a. rating or the maximum current on short-circuit.

Protection of Switchgear and Busbars.

This portion of the supply system is so well made and free from rough treatment that there is very little to go wrong except through carelessness, and in very many cases no special protection is given. Busbar faults are the most serious of all supply-system faults and will almost invariably shut the whole station down and dislocate synchronous machinery on the mains. Substation busbars and switchgear are covered by the overload feeder protection at the power-station end. It is partly to deal with these faults that feeders and generators are equipped with time-element overload relays. In large power stations the possibility of a complete shut-down is minimized by sectionalizing the busbars by means of reactance coils.

Reactance coils.—The whole question of the use of reactance coils in the protection of alternating-current circuits opens up a subject large enough for a separate paper. Although reactance coils play an important part in the protection of supply systems, particularly in limiting the severity of faults, the considerations governing their use have practically no effect on the characteristics of protective gear as outlined in this paper. The subject will therefore not be dealt with further.

Transformers.

There are in general three types of transformers used in protective gear. The Merz-Price "balanced current," plain overload protection, etc., require ordinary current transformers. They must be carefully and uniformly built so as to balance well, but otherwise they embody no special feature. For Merz-Price feeder protection special transformers are necessary. These transformers are current-operated on the primary, while on the secondary their voltages are balanced, so that the transformer is in the nature of a current transformer on one side and a potential transformer on the other. The difficulties in balancing this type of transformer have already been referred to.

For "split conductors," "self-balancing" and "core-balancing" systems the transformers are all of the same type. The secondary winding is directly connected to the relay. The required volt-ampere output is therefore definitely fixed, so that the primary current required to give this output is also constant for a given size of transformer. This means that the fault setting is more or less constant whatever the k.v.a. rating of the apparatus to be protected.

Conclusion.

No general rules can be laid down as to the best system of protection or even as to the best type of system. The various operating problems must be considered individually for each case, not only as regards present requirements but, as far as possible, taking future requirements into account. It is the consideration of future alterations and extensions which brings out the advantages of the balanced type, where each unit of protection is self-contained and works quite independently of other units. Gear of this type can be installed all over a system with the sure knowledge that its operation is independent of future additions, and, conversely, a network can be laid out without any regard being paid to the protective system.

It is often possible to effect great saving in the more economical and efficient use of apparatus and mains by choosing the proper type of gear. For instance, there will be considerably less need for duplicate feeders, spare machinery and apparatus. In fact these considerations are so important that the actual cost of the protective gear should be the last thing to be considered.

Progress in the development of protective gear is rapid. For this progress to be in the right direction, manufacturers must have a clear knowledge of operating conditions, whilst supply-system engineers should appreciate the technical difficulties involved in meeting practical requirements. There should therefore be close co-operation between them, as it is only by working in conjunction that the most satisfactory results will be obtained.

THE PRINCIPLES OF SCIENTIFIC ILLUMINATION.

By C. E. Webb, B.Sc., Student.

(*Abstract of paper read before the* Students' Section, 9 *May*, 1919.)

Introduction.

It is proposed in the following paper to discuss the general principles underlying the science of illumination, rather than the details of the various systems of lighting at present in use.

The fundamental point which it is desired to emphasize throughout is that illumination is essentially a physiological problem. Formerly the physical or energy aspect of the question was unduly prominent and too much attention was devoted to physical and semi-physical methods of treatment, but recently it has been more and more widely recognized that such treatment is inadequate, and that the effectiveness of a lighting installation depends essentially on physiological considerations.

Measurement of Light and Illumination.

It is proposed first to consider the various quantities dealt with and the units in which they are measured. It is to be noted that these quantities all involve a subjective or physiological element and consequently the units employed cannot belong to the purely objective C.G.S. system but must be based on some arbitrary standard.

Until the last few years almost all theoretical work in illumination was based on the idea of intensity and the fundamental unit was the candle-power. Lamps were rated either by mean horizontal candle-power (M.H.C.P.), mean hemispherical candle-power or mean spherical candle-power (M.S.C.P.), the opinions of experts as to the value of each of these as a basis being widely divergent. Calculations of illumination were made from polar curves of candle-power distribution by point-to-point methods.

Recently, however, the intensity basis has been almost completely abandoned and the conception of luminous flux has been introduced as the basis for both theoretical and practical work.

Physically considered a light-source emits ether waves representing energy which may be measured in ergs, joules or foot-pounds; physiologically it may be considered as emitting luminous flux which must be measured in terms of some unit involving a physiological element. The relation between the two measurements depends on the sensitiveness of the eye to the particular type of light emitted and varies with the wave-length, i.e. the colour, of the light according to the well-known luminosity curve of the human eye. Hence for composite light the energy intensity at each wave-length must be multiplied by a factor proportional to the corresponding ordinate of the luminosity curve in order to give the quantity of luminous flux in each part of the spectrum.

The unit of flux, which is now the fundamental unit for practically all work on illumination, is the lumen and is the flux emitted by a uniform source of unit intensity (as shortly to be defined) within unit solid angle, i.e. the flux falling on a unit area on the surface of a sphere of unit radius with its centre at the source.

It follows from the above definition of the lumen that the unit of intensity, the candle-power, is 1 lumen per unit solid angle and that a source of 1 M.S.C.P. emits 4π lumens.

The candle-power is arbitrarily defined by means of some standard, such as the Harcourt pentane lamp or the Hefner lamp, the horizontal intensity of which is accurately known under specified conditions of burning, when the necessary corrections are made for the barometric pressure, humidity, and oxygen and carbon-dioxide contents of the atmosphere.

It will thus be seen that, in practical photometric work, the candle-power remains the fundamental unit since it alone is directly reproducible from specifications. In practically all other cases it has been replaced by the lumen.

The illumination of a surface is the flux density incident upon it. The usual unit of illumination is the foot-candle and is the illumination on a surface placed normally at a distance of 1 foot from a source of 1 candle-power. From the above definition of the lumen it is clear that an incident flux density of 1 lumen per square foot gives an illumination of 1 foot-candle. The foot-candle is an unscientifically-named unit, since it is not, like the foot-pound or the watt-hour, a product of two factors denoted by the two parts of the name, and it would be preferable from the scientific point of view to replace it by one of the metric units, the lux or the phot, equivalent respectively to 1 lumen per square metre or per square centimetre, or their derivatives. The foot-candle is, however, so universally employed in this country that it is not likely to be given up until the metric system of units is generally adopted.

Closely related to the illumination of a surface is its brightness. This, for a perfectly diffusing surface, the radiation from which is distributed according to the cosine law, is constant in all directions and is equal to the light flux density emitted whether the surface is self-luminous, reflecting or transmitting.

In the two latter cases it is evident that the brightness is equal to the illumination multiplied by the coefficient of reflection or transmission, and may thus be expressed in foot-candles or in the corresponding metric units. The chief of these is the lambert, which has been employed in America, though as yet it has hardly been introduced into this country. It is the brightness of a perfectly diffusing surface emitting 1 lumen per square centimetre.

For secondary sources this is a very large unit and the milli-lambert is generally used. For surfaces which do not diffuse their light according to the cosine law, the brightness in any direction is no longer equal to the lumens emitted per unit area, but it is equal to the apparent lumens per unit area, i.e. to the lumens which would be emitted by a perfectly diffusing surface of the same brightness. Brightness may also be expressed in apparent candle-power per unit area, which is the candle-power in the direction considered, divided by the projected area of the surface. This method of measuring brightness is generally used for self-luminous surfaces, but values expressed in one system can be readily translated into the other, since in all cases:—

Apparent lumens per unit area $= \pi \times$ apparent c.p. per unit area, or, in the metric system, lamberts $= \pi \times$ apparent c.p. per sq. cm.

Thus, instruments such as will shortly be described, which measure illumination by observation of the brightness of a white diffusing screen, may readily be arranged to give direct readings of apparent candle-power per unit area by allowing for the coefficient of reflection of the screen and for the constant factor π.

Practical Methods of Measurement.

The standard method of measuring candle-power by direct comparison with a standard or sub-standard lamp in a bench photometer is so well-known as to need no detailed description.

The measurement of flux involves an integration of the candle-power in all directions. Owing to the varying area of zones taken at different angles, however, this summation cannot be performed directly by averaging the ordinates of the polar curve. In general the integration is performed by means of one of the well-known analytical methods or their graphical equivalents, such as Rousseau's or Kennelly's method, applied to the polar curve. The flux of a lamp may also be found experimentally by the use of integrating mirrors, arranged to weight the intensity at each angle to the proper extent, or by means of the well-known Ulbricht globe.

The development of instruments for the measurement of illumination forms one of the most striking features of recent progress in the science of illumination. The ordinary bench photometer actually compares illuminations, and the illumination photometer is thus identically the same in principle. It is modified in form, however, to provide a portable instrument suitable for measuring the illumination at any point conveniently without any pretence to a high degree of accuracy. Such instruments may be fitted with an internal screen to receive the illumination to be measured, or the screen may be detached so as to be more readily placed in any desired position and then viewed through the instrument. The following are some of the chief types of illumination photometer at present in use:—

(1) The Lumograd of Messrs. Siemens Bros. is of interest as being a link between the bench photometer and the illumination photometer. It is in fact a miniature bench photometer in portable form, containing a small electric lamp, the distance of which from a photometer screen is varied by means of a rack driven from a spindle which also carries a pointer moving over a dial. The screen consists of two sheets of celluloid separated by a thin sheet of lead, one side being illuminated by the lamp and the other receiving the illumination to be measured. The two sides are viewed simultaneously by means of mirrors in the usual way. A 2·5-volt lamp is used, connected through a press switch to a 1·5-volt dry cell of large capacity to ensure constancy of voltage and candle-power over a long period. Absorbing glasses, which may be placed on either side of the screen, greatly extend the range of intensities measurable. The instrument is chiefly suitable for measuring the illumination normal to the direction of the source, from which the candle-power may at once be found by applying the inverse-square law, and polar curves may readily be obtained.

(2) The Trotter photometer (Fig. 1), one of the first types to be developed, has a mat-white screen (A)

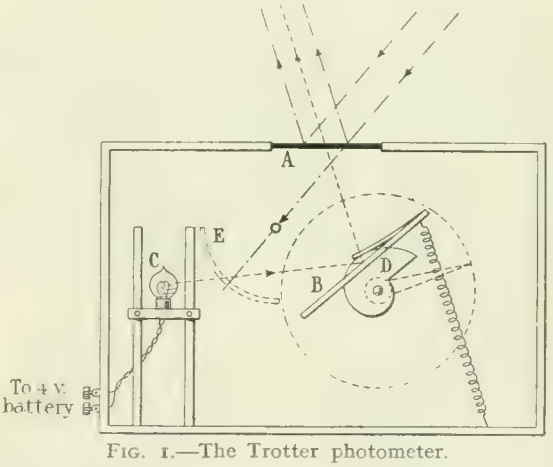

Fig. 1.—The Trotter photometer.

on the top of the case, on which falls the illumination to be measured. By looking through a hole in this screen in a direction approximately 20° from the vertical and definitely fixed by adjusting a pointed projection within in line with the slot in the screen, a second internal screen (B), illuminated by a small electric lamp (C), may be compared with the external screen. Balance is obtained by turning a milled head which tilts the internal screen, thereby altering the angle at which the light falls on it and moving a pointer over a dial. The screen is tilted by means of a snail cam (D) to give a wider scale at low illuminations. The lamp is run from a 4-volt accumulator battery, reliance being placed on the constancy of the cell voltage during discharge to maintain the candle-power constant, although if special accuracy is desired the voltage may be measured and the lamp set accordingly on a special scale. For measuring the horizontal illumination, which is usually adopted as a criterion of the total illumination, the instrument may be adjusted by a spirit-level and the angle at which the light is being received, which is required if the candle-power is to be deduced from the readings, is then given by the shadow of a small pin on an angular scale (E). If adjusted to measure the

normal illumination, the angle of inclination to the vertical is recorded by means of a small steel ball running on a circular ledge on the side of the case.

(3) The Luxometer of Messrs. Everett, Edgcumbe & Co. is a modification of the Trotter instrument. The size is considerably reduced and the instrument is extremely portable. The screen on top of the case is replaced by a separate screen carried on a sliding strip which is mounted on the case, or by an entirely detached screen placed in any desired position. This screen is viewed directly through an eyepiece, half the field of which is occupied by a mirror reflecting an image of an internal screen illuminated by a 4-volt lamp and

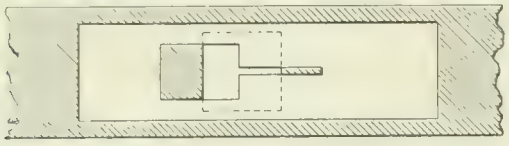

FIG. 2.—Shutter of lumeter, showing shape of slot.

tilted to obtain balance by turning a milled head, exactly as in the Trotter instrument. The Luxometer may be directed at any surface whatever to measure apparent brightness in foot-candles, but for illumination and candle-power readings it must be used with a mat-white surface of standard reflecting properties.

(4) The Holophane Lumeter is based on the same principle and again employs a separate mat-white screen which is viewed directly through the eyepiece and through a small circular hole in a screen illuminated by an internal

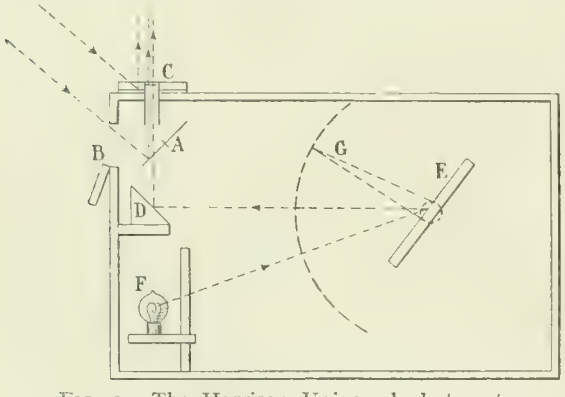

FIG. 3.—The Harrison Universal photometer.

lamp. As before, the lamp is run on a 4-volt accumulator battery without any means of adjusting the candle-power, but the method of controlling the illumination produced is novel. An arm outside the case, carrying a pointer provided with a direct-reading scale, moves a shutter in which is an irregular aperture across an opal screen. The aperture is ten times as wide for half its length as for the other half (cf. Fig. 2) and by this means the scale is much expanded for low illuminations. By inserting either or both of two absorbing glass screens the scale may be multiplied by 10, 100, or 1,000, thus giving a very extensive range. Like the Luxometer, the instrument may be readily employed to measure brightness.

(5) The Harrison Universal photometer of Messrs. Elliott Brothers (cf. Fig. 3) possesses the distinctive feature of a flicker disc for comparisons when there is a colour difference between the illumination measured and that given by the standard. The sector disc (A), which is rotated by an air-blast from a hand-operated air-pressure bulb, is mounted at an inclination of 45° just inside a small door (B) in the case, and is viewed through an eyepiece (C) from above. Behind the sectors is a mirror (D) reflecting an image of an internal screen (E) illuminated by a standard 4-volt lamp (F) run from accumulators. To obtain balance the inclination of the screen is adjusted by turning an external pointer (G) until the flicker disappears. The flicker disc may also be clamped to occupy half the field, and readings made by direct comparison. In either case the disc should be placed normal to the light source, though a correction may be made for any deviation from this condition from the reading of a clinometer on the instrument. To measure total horizontal illumination the flicker disc is not used and the eyepiece is removed, uncovering a white screen, through a perforation in which the internal adjustable screen may be viewed. Three ranges are available by varying the position of a plug completing the lamp circuit through different resistances. This method is not generally desirable owing to the colour changes produced, but with the flicker disc this is not important.

INTENSITY OF ILLUMINATION.

The most obvious requirement in a lighting installation is the provision of an adequate intensity of illumination. Generally in artificial-lighting systems it is not possible to provide intensities approaching those obtained from daylight. Fortunately, however, this is not essential, as owing to the power of adaptation of the eye a much lower value will give satisfactory vision. The intensity required varies greatly in different classes of illumination and experience is often the best guide, but the following table gives some fairly well-established values of mean horizontal illumination, although considerable latitude must be allowed in individual cases.

Places illuminated	Foot candles
Suburban residence streets	0·02
Well-used business streets	0·2
Very important squares or street-crossings	0·5
Yards, corridors, etc.	0·5–1·0
Machine shops and offices with additional local lighting	1–2
Heavy assembly work, power houses, etc.	2–3
Machine shops and offices without local lighting, schools, libraries, etc.	3–5
Drawing offices, typesetting, etc.	8
Engraving and very fine work	10
Operating table	12
Shop-windows, advertisements, etc. (the figure depending on colour of surfaces illuminated and brightness of surroundings)	3–15

In the calculation of illumination two methods may be adopted. The older point-to-point method involves

the separate calculation of the horizontal illumination at a number of points, and the plotting of the results either as linear distribution curves showing the variation in illumination along one or more straight lines, or as contour curves connecting points of equal illumination. It is still used in connection with street-lighting, but has been almost entirely replaced by the newer flux method for indoor calculations.

In this method the illumination required is found from the table and is multiplied by the area to be illuminated, giving the total number of lumens required on the working plane. To determine the total flux to be generated use is now made of a "coefficient of utilization," which is the ratio of flux utilized on the working plane to flux generated by the lamps. The value of this coefficient depends on the system of lighting adopted, on the ratio of the ceiling height to the width and length of the room, and on the reflecting properties of the ceiling and walls. This last factor is of special importance, the reflection from light ceiling and walls in some cases adding from 50 to 70 per cent to the flux utilized. Allowance should also be made for depreciation due to the inherent falling off in candle-power during the life of the lamp and to the effect of dirt collecting on the lamps and reflectors. A suitable spacing for the size of the room and type of lamp used is then decided upon, and from the number of units needed and the total flux to be supplied the size of each unit may be calculated.

Avoidance of Glare.

The subject of glare is still in a somewhat confused and indefinite state owing to the absence of an adequate scientific basis of exact knowledge as to the physiological actions taking place. It is probable that two or three distinct effects are classified together under the heading of "glare" and a satisfactory definition is therefore difficult. Perhaps one of the best, because the most general, is that given by the American I.E.S. Committee on Glare (1915) which defines glare as "Light shining into the eye in such a way or of sufficient quantity as to cause discomfort, annoyance or interference with vision." The chief causes of glare are excessive brightness of sources or other surfaces, excessive contrast of illumination, flicker, and specular reflections.

(*a*) *Excessive brightness.*—Most modern illuminants, especially electric lamps, have a very high intrinsic brilliance, and the presence of such sources near the line of sight causes a contraction of the pupil with consequent reduced sensitiveness of the eye, and also produces fatigue of the retina which still further diminishes its sensitiveness. Hence such lamps should always be provided with accessories in the form of reflectors, refractors, or diffusing globes and bowls to reduce the brightness (this often improving the light distribution) and should be placed as high as possible so as to be well removed from the line of vision. The increased brightness of the latest types of lamp has also led to a large development of the well-known indirect and semi-direct systems of lighting, in which all or most of the light is thrown on to the ceiling and thence reflected into the room. Formerly it was considered that a brightness about equal to that of the sky, or from 2 to 3 candles per sq. in., was satisfactory, but it is now recognized that a still lower value is desirable and, for schools and rooms in which people are engaged for long periods in reading or writing, a brightness not exceeding 250 milli-lamberts or about $\frac{1}{2}$ candle per sq. in. is recommended.

(*b*) *Excessive contrast of illumination.*—The effect of excessive intensity depends largely on the degree of contrast between the bright area and its surroundings, and both with sources and illuminated surfaces the ratio of the brightnesses of the area and its surroundings, particularly of the contiguous surfaces, should be kept small. The need for this arises from the eye-fatigue resulting from the continual attempts of the eye to adapt itself to the brightness of the surface viewed and to the different conditions obtaining at various parts of the retina when the brightness of the surface viewed is not uniform. A maximum brightness ratio of 100 : 1 is generally aimed at, although the value permissible depends on the intensity of illumination, and a ratio of 20 : 1 should not be exceeded for neighbouring surfaces.

(*c*) *Flicker.*—This may be regarded as successive contrast and is harmful owing to the fatiguing effect on the eye of repeated attempts at adaptation.

(*d*) *Specular reflection.*—This is reflection from polished surfaces, such as furniture or glazed wall-paper and writing paper, and is a very fruitful and insidious cause of glare. Since it obeys the law of regular reflection, it may be largely eliminated by judicious control of the direction from which the light is received.

Diffusion of Illumination.

In addition to the diffusion of light which is desirable in order to reduce brightness it is generally also required to diffuse the illumination so that it is received from a number of different directions. This is of value in avoiding the "high-lights" due to specular reflection, which have just been referred to, and also in reducing the sharpness and intensity of the shadows produced. This object is very effectively attained in indirect and semi-indirect lighting, while with direct lighting systems the use of a number of separate units will achieve the same result.

Uniformity of Illumination.

The need for uniformity of illumination to avoid glare has already been referred to. In many cases, for example in large offices, a high degree of uniformity is required in order that work may be carried on at any point, and the method of securing such uniformity will now be briefly considered. On the old point-to-point method, the illumination at the points of maximum and minimum intensity had to be calculated and the installation arranged to bring this ratio down to the required value. Under present conditions, accessories have become so standardized that for any given type the ratio of spacing distance to mounting height to provide a satisfactory degree of uniformity is known, and if the unit is used with appropriate spacing ratio no further consideration need be given to the uniformity. The spacing may always be reduced below the standard

value without affecting the uniformity, but if higher illumination is required it is generally more economical to use a large unit of the same type at the maximum spacing permissible, owing to the greater installation cost with a larger number of units.

In street-lighting the problem is somewhat different, owing to the almost complete absence of light reflected from the surroundings, which in the case of indoor lighting greatly improves diffusion and uniformity of illumination. The intensities dealt with are much lower and a high degree of uniformity is neither required nor economically obtainable. Two distinct cases have to be considered in street-lighting: the high-intensity lighting provided in important squares and street-crossings, and the moderate and low-intensity lighting provided in the great majority of streets. In the former case the eye is in the same state as under daylight conditions and is able to discriminate fine detail and differences of colour. Sufficient light is provided to give a fairly high degree of uniformity, and the conditions approximate more closely to those obtaining in indoor lighting. In the second case the eye becomes what is known as "dark-adapted" and vision is effected chiefly by contrast of light and shade with very little, if any, perception of colour.

In this state, therefore, objects are chiefly distinguished as silhouettes. The lighting in streets where this condition exists may be purely beacon lighting, intended merely to mark out the way, no attempt at uniformity being made, or a sufficient illumination for safety may be required at all points. In the latter case, with such spacing of units as the cost of standards and installation will allow, the polar curve necessary for uniform illumination is a very flat loop. To obtain such a curve with a reflector is practically impossible and would involve the use of an extremely large shallow dome. Refractors are therefore commonly employed and give a very satisfactory distribution, but even with these it is difficult to obtain a ratio of maximum to minimum illumination of less that 10 : 1. Fortunately, however, greater uniformity is not required, as it is found that at points of low illumination the silhouette effect is more marked, while the brightness of the street surface is but little diminished. Moreover, glare from the lamps, which is liable to occur with refractor units, is considerably reduced by using wider spacing.

Colour.

The question of colour in lighting is again essentially a physiological problem, as although the colour is correlated on the physical side with the wave-length of the radiations, subjective elements play a very large part in determining the colour value of the light. Spectrum data are always valuable but, owing to the eye being synthetic and not analytic in its operation, such information is, in our present state of knowledge, by no means final.

In considering the colour of the illuminant the psychological element is of importance. Certain colours are fairly well recognized as "warm," "cold" or "neutral" and as having a cheering or depressing effect.

The colour of the surroundings must also be considered in this connection, since after selective reflection the colour composition of the reflected light differs considerably from that of the light given by the lamp, and the colour of the resultant illumination may thereby be modified. By judicious combinations of the colour of the illuminant and the colour of the surroundings suitable and pleasing colour effects may be produced. Surroundings of a very pronounced tint, especially if similar to that of the illuminant, are generally undesirable, as by repeated selective reflection the light ultimately utilized becomes too markedly of that colour. .

The provision of monochromatic light is often useful in increasing visual acuity since, the eye not being an achromatic lens combination, rays of different colours cannot simultaneously be accurately focused, and a blurred image is produced. This is important for drawing-office and other fine work for which approximately monochromatic light is often used, the shorter wave-lengths being generally preferred.

Another important colour property of the eye is the well-known Purkinje effect. At intensities below about 0·1 foot-candle the eye becomes relatively more sensitive to bluish light, the curve of luminosity shifting considerably towards the blue end of the spectrum (cf. Fig. 4). It should receive consideration in the case of low-intensity illumination, as in street-lighting or the detection of lights at a distance, such as lighthouses or railway signals. The effect is, however, often counterbalanced by the "yellow spot effect," in which, as an object recedes, its image occupies a smaller area on the retina and coincides more entirely with the "yellow spot," which is particularly sensitive to yellowish light. Thus at greater distances a yellow light tends to become brighter than a blue one. Furthermore, the greater penetrating power of red and yellow light in fogs and dense atmospheres often renders them preferable for distance work.

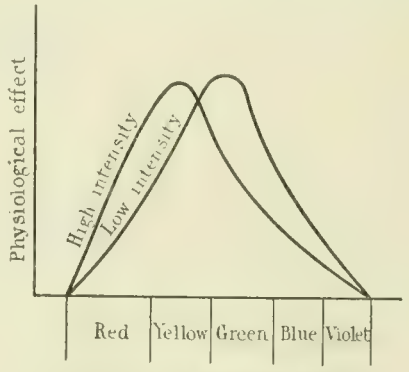

Fig. 4.—The Purkinje effect

Another very important branch of coloured illumination is the production of "artificial daylight" of standard colour for work involving accurate colour discrimination. Two different daylight standards have been proposed, viz. north skylight, and noon sunshine. The former is considerably bluer than the latter and is used for the most accurate work, but it is more difficult to obtain. Artificial daylight may be obtained directly by the use of suitable sources such as the "Moore"

carbon-dioxide lamp or a combination of a mercury arc and tungsten glow-lamp, but the tendency at the present time is rather to use a lamp giving light of only approximately the correct colour and to modify the colour as required, by means of selectively absorbing screens. Arc lamps and half-watt lamps fitted with bluish screens to absorb the excess of red light from the lamps are both suitable. To give north skylight a large proportion of the light has to be absorbed—from 75 to 85 per cent with half-watt lamps—but for noon sunlight, which is satisfactory for all except the most accurate colour-matching, the absorption need not exceed 50 per cent, which is not serious with high-efficiency illuminants.

Efficiency.

In engineering work the term "efficiency" denotes the ratio of energy output to energy input. The quantity commonly known as the "efficiency" of a lamp—the watts per candle—is unscientifically named, being, in fact, a consumption; and, in addition, the use of the candle-power is very unsatisfactory, as it provides no accurate measure of the illuminating value of the lamp. The introduction of the total flux gives a more useful quantity, and efficiencies are now being expressed in lumens per watt. It seems undesirable, however, to apply a word which has become generally standardized for a ratio of energies, to a quantity of a different character, and it would be well if some other term, such as "efficacy," could be used to denote this ratio.

Moreover, although the best numerical value which can be employed, the lumens per watt do not provide a final measure of the effectiveness of the system, since two systems giving the same number of lumens per watt may differ very widely in the value of the illumination obtained owing to glare, colour effects, degree of diffusion etc., which cannot be numerically expressed. Thus, although in the interests of economy the efficiency must be carefully considered, its importance is relatively small, and other requirements of good illumination should not be sacrificed to it.

Comparison of Candle-power and Flux Basis.

Having considered the chief elements involved in the production of good illumination it may be well to summarize the advantages of treating the subject from a flux basis rather than a candle-power basis. The principal advantages in practice are as follows:—

(1) *Rating of lamps.*—Formerly the M.H.C.P. rating was fairly satisfactory, as the ratio of the M.H.C.P. to the M.S.C.P. (and hence to the total lighting power of the lamp) was fairly constant. With the greater variety of illuminants at the present day and the extensive use of half-watt lamps with spiralized filaments of various forms giving a wide range of distribution curves, however, this constancy is no longer maintained and the M.H.C.P. is liable to be very misleading. Furthermore the candle-power can be readily increased in any given direction by silvering the bulb in a suitable manner and such "faking" of lamps has actually been carried on in the past, while the candle-power rating is no criterion of what the lamp can do when used with a reflector. The flux rating on the other hand is not subject to manipulation and is unaltered by the use of reflectors and accessories except for the small absorption which occurs.

Projection units represent an extreme case of the magnification of candle-power without increase in flux. It was these advantages of lumen-rating which led to the introduction of the lumen in practical work, and at present it is always used by lamp-makers to express the illuminating value of their lamps. It is only a matter of time, until the general engineer, the contractor and the public are educated up to its use, for the lumen to replace the candle-power completely in all references to the size and power of illuminants.

(2) *Easy calculation of illumination.*—As has been pointed out, the relation between the flux in lumens, the area illuminated and the mean illumination produced is extremely simple, and the introduction of flux avoids the troublesome point-to-point calculations necessary on a candle-power basis.

(3) *Easy calculation of absorption of accessories, etc.*—To determine the absorption of a lamp accessory or of any surface whatever, it is only necessary to measure the flux with the accessory or other surface removed and then to measure it again with it in place. The ratio of these two quantities gives the reflection or transmission coefficient, and its difference from unity is the absorption. No such simple relation holds with candle-power, as the distribution is generally altered.

(4) *Diffuse sources.*—Candle-power methods are based on the assumption of point-sources, always an approximation, and now not even a good approximation. With the surface-sources so largely used at the present time, as for example in indirect lighting, the flux conception is of great value, as its application is in no way affected by the fact that the inverse-square law no longer holds. Even the diffused light from the sky can be similarly treated, and it is a further advantage to be able to deal with problems of daylight and artificial lighting on the same lines.

Conclusion.

The subject of illumination has become highly specialized, and it is impossible for the average electrical engineer to study at all deeply the problems of good lighting, but the author feels that every engineer should have some knowledge of the general principles of scientific methods of illumination, since it is only through the responsible engineers appreciating the need for improvement that factory and other classes of lighting, much of which is at present very badly carried out, can be raised to a more satisfactory standard.

PROCEEDINGS OF THE INSTITUTION.

650TH ORDINARY MEETING, 13 MAY, 1920.

(Held at the Institution of Civil Engineers.)

Mr. ROGER T. SMITH, President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting of the 29th April, 1920, were taken as read, and were confirmed and signed.

The list of candidates for election and transfer approved by the Council for ballot was taken as read and was ordered to be suspended in the Hall.

A paper by Mr. S. Evershed, Member, entitled "Permanent Magnets in Theory and Practice" was read and discussed, and the meeting adjourned at 7.55 p.m.

48TH ANNUAL GENERAL MEETING, 20 MAY, 1920.

(Held at the Institution of Civil Engineers.)

Mr. ROGER T. SMITH, President, took the chair at 5.30 p.m.

The minutes of the Ordinary Meeting of the 13th May, 1920, were taken as read, and were confirmed and signed.

The President announced that the scrutineers (Messrs. F. B. O. Hawes, Professor J. T. MacGregor-Morris and Mr. W. E. Warrilow) appointed at the Ordinary Meeting of the 29th April, had reported to him that they had examined the ballot papers for the election of new Members of Council, and that the following had been found to be duly elected :—

President : Mr. LL. B. ATKINSON.

Vice-Presidents : Dr. W. H. Eccles, Mr. J. S. Highfield, and Mr. S. L. Pearce, C.B.E.

Honorary Treasurer : Sir James Devonshire, K.B.E.

Ordinary Members of Council : Mr. F. Gill, O.B.E., Mr. P. V. Hunter, C.B.E., Mr. A. H. W. Marshall, Mr. W. Noble, Dr. A. Russell, and Mr. C. Vernier.

A vote of thanks was passed to the scrutineers of the ballot.

Messrs. D. R. Broadbent and P. Harris were appointed scrutineers of the ballot for the election and transfer of members, and, at the end of the meeting, the result of the ballot was declared as follows :—

ELECTIONS.

Members.

Davidson, William Ralph.
Elwell, Cyril Frank.
Linton, John Richard W.
Midgley, Harold Edward.
Migotti, Lorenzo W.
Round, Henry Joseph, Capt., M.C.
Tennant, Norman Scholefield, M.Sc.
Turner, Laurence Beddome, M.A.

Associate Members.

Allan, William.
Amor, Frank.
Badger, William James.
Barker, Ernest Francis, W., Lt.-Col.
Barnard, Alfred George S.
Bastable, Herbert Arthur.
Beaumont, Arthur William
Buglass, John Ferguson.
Carter, William Robert.
Cartland, Reginald Avonel.
Clayton, Harry.
Cousins, Alban Bertie.
Curtis, Harry Stuart, B.Sc.
Fraser, Andrew Moore.
Gerrald, Harold, M.Sc.
Green, Frederick William, B.Sc. (Eng.).
Green, Horace.
Gubbins, Thomas Russell, B.Sc.
Hamilton, Benjamin Henry N. H.
Harris, Frederick Pool.
Hodgkinson, Thomas Gerald.
Kirkpatrick, George Louis.
Langrish, Noel George.
Lawrence, Nathaniel.
Lemmon, Samuel William.
Macdonald, George.
McKeown, John Alexander.
Marler, Walter Sydney.
Marshall, George.
Norfolk, Thomas Lord.
Patterson, Robert Norman
Pedrick, Thomas.
Rudge, Edwyn Ross.
Shuttleworth, Charles Irwin.
Siviour, Sidney Reginald.
Stobie, Victor.
Thomson, Alexander, Jun.
Tokuda, Inosuke, Commander, I.J.N.
Van de Merwe, Daniel Stefanus, B.Sc. (Eng.).
Williams, David Gwyn.

Graduates.

Bailey, Albert Clifford.
Bennett, Hedley Harry G.
Bremner, Francis Donald H., B.A.
Bulman, Christopher Howard.
Catton, Harold.
Chamen, William Francis.
Clare, Charles Frederick.
Coffee, Randall.
Conville, Alfred.
Denton, Robert Alan E.
Finney, Percival Francis.
Greig, George.
Harris, Augustus Frederick.
Hilton, Christopher Frederick.
Horne, Walter.
Hutton, Frank Willoughby.
Ingham, Herbert Edward.
Lovell, Edward Philip.
Machin, Ben.
Nicholson, William Edward B.
Physick, Nino William.
Polson, William Fairlie.
Poore, William Graydon, B.A.
Read, Ralph Sidney.
Saucedo-Redondo, Godofredo.
Skidmore, Frederick William.
Tremain, Arthur Geoffrey.
Walker, Charles Abraham O.

Students.

Adams, Basil Norwood.
Alder, Charles Daniel.
Allman, Edward James.
Arzonie, Walter Arnoldus.
Atkins, Roy Edward.
Atkins, William Thomas J.
Barrett, George Edward.
Barthet, Esprit Eugene T.
Bates, Llewelyn Archer.
Bell, Leslie Mandell T.
Bessant, Stanley James.
Birt, Ronald.
Bowden, Lionel Maurice.
Braid, David Halyburton.
Brain, Vivian James F.
Bristow, Ralph Eric.
Brown, Harry.
Bullock, Percy Charles.
Burgess, William.
Burnie, Eric.
Carey, Windham Francis, B.Eng.
Carson, William Noel.
Causbey, Reginald John.
Childs, John Stanley E.
Colebrook, Francis Morley.
Collyer, Harold James.
Cook, Robert Middleton.
Cooper, William Fordham C.
Cragg, Robert Ira.
Damp, John William.
Davies, Wallace Dunmall.
de Lancastre, Pedro.
Denné, Frank Ernest.
Donovan, Eric Theodore G.
Doxat-Pratt, Maurice.
Elliott, Noel.
Emms, Sydney Albert G.
Fearon, Philip Vivian.
Ferris, Clarence Henry.
Franks, Henry Bertram S.
Galea, Robert F.
Girvan, William, Jun.
Goodchild, Norman Walter
Gorham, Maurice Laver.
Grainger, Gordon.
Greenbank, Joseph William.
Grimmer, George Skeffington M.
Harrison, Arthur Casswell.
Hope-Tait, Hamilton.
Hunter, Norman.
Johnson, Leslie William.
Johnston, Walter Newman.
Jolly, Edward Ernest.
Jordan, William Stewart.
Knowles, Horace Albert.
Lambert, Leonard John G.
Leakey, Reginald Edward.
Lennox, Edward Cecil.
Linford, Edna Joan (Miss).
Long, Arthur Leslie.
Long, John Noble.
Lovely, William Stanley.
McVie, Allan.
Martin, Douglas William C.
Mathews, Denys Cyril H.
Matt, Hermann Albert.
Millington, Stanley.
Montague, William McAdam T.
Neal, Albert Frederick.
Newland, Ernest William J.
Nicholson, Graham Franklin.
Pamment, Frank Townsend.
Poole, George Arthur H. E.
Priddle, Albert Thomas.
Pryce-Jones, Hubert.
Radcliffe, Charles Joseph, B.N.
Roberts, Morris Glyn.
Robins, John Henry.
Scott, John Dunbar.
Seager, Alfred Charles.
Seccombe, Alfred John L.
Sharp, Henry Poland.
Short, William James C.
Skinner, Walter Reginald T.
Stafford-Ball, Hereward Thomas.
Steel, Harry Gordon.
Stewart, James Urquhart.
Stopford, Charles William.
Stuart, Joseph Rosslyn.
Tassell, Reginald William.
Telfer, John.
Thomas, Horace Augustus.
Tiedeman, Thomas.
Tolton, William George.
Wagstaffe, Charles Frederick A.
Ward, Leslie Edward.
Watkin, Harold.
Whalley, Rupert Harold.
Winder, Reuben Frederick.
Withrington, Herbert Henry.
Wright, Maurice McGill.

Associates.

Griffiths, Martin.
Hosgood, Octavius Sidney.
Sloan, George Andrew.

TRANSFERS.

Associate Member to Member.

Allan, Percy Frederick.
Ayton, Reginald.
Brettelle, Clifford Oswald.
Coates, William Anselm.
Dinham-Peren, Arthur Edward H.
Edmundson, John Edgar.
Ellis, Alfred George.
Ferguson, Samuel.
Gibson, Samuel Cameron.
Highfield, William Eden.
Hirst, John, B.A.
Hutchins, Thomas William S.
James, William Lewis.
Kemp, Philip, M.Sc. (Tech.).
Kennett, Alick James N.
Lewenz, Henry Ivan.
Lewis, Lucien Alexander.
Longman, Robert Martin.
Marr, William Bell, B.Sc.
New, Charles George M.
Nimmo, Henry W., Capt., R.E.
Paton, George Kinnaird.
Phillips, Alexander Dick.
Salter, Glynn.
Taylor, John Dean.
Thompson, John Lindley, M.Sc.
Thorp, Edgar Leslie.
Wayte, William Joseph.
Woods, Herbert Frank G.

Graduate to Associate Member.

Khanna, Jagannath Prasad.
Monks, Cuthbert Edgar.
Neale, Reginald Edgar, B.Sc.
Webb, Richard Jeffrey.

Student to Associate Member.

Jackson, William Gordon C.
McMahon, Reginald Artane.
Prescott, James Cuthbert.

Associate to Associate Member.

Brown, Walter, M.A., B.Sc.

Student to Graduate.

Breeze, Robert Bagot.
Bridge, Albert.
Dos Ramos, Herculano Lourenco.
Leeson, Brian Ernest.
Macpherson, A. W. Roy.
Morris, Charles Isted.
Puttick, Harold Walter.
Sanyal, Kshitish Chandra.
Thomas, Alan Ormond.
Thomas, William John.
Young, William.

The President, after summarizing the Annual Report of the Council for the year 1919–20 (see page 308), moved: "That the Annual Report of the Council for the year 1919–20 as presented be received and adopted."

The resolution was seconded by Mr. J. Shepherd, put to the meeting and unanimously adopted.

Sir James Devonshire (Honorary Treasurer) then moved the following resolution: "That the Statement of Accounts and the Balance Sheet for the year ended 31st December, 1919, as presented be received and adopted." In moving the resolution Sir James Devonshire said: "I desire to refer to the fact that this is my first presentation of the accounts since the regrettable resignation of Mr. Kingsbury, who so ably fulfilled the office of Hon. Treasurer to the great advantage of the Institution from 1915 to 1919, and by whom a high standard of excellence has been set me which it will be my sincere desire to follow to the best of my ability.

"*Income and Expenditure.*—As will be seen by the printed report which has been issued to members (see

page 320), there is a margin to the good on the Revenue Account for 1919 of £1,495 3s. 3d. after making full provision for contingencies; and this amount, which has been carried to the credit of the General Fund, compared with £1,270 11s. 5d. in 1918 shows an increase of £224 11s. 10d. The total expenditure for 1919 was £24,097, as compared with £17,376 in 1918, an increase of £6,721, the principal items occurring under the heads of 'Management' which is up by £3,328, the *Journal* which is responsible for an increase of £1,038, and the Territorial Centres, Meetings, etc. On the other side of the Account the income shows a gratifying expansion by reason of the fact that the subscriptions for the year were £19,532 1s. 4d. as against £16,344 2s. 2d. for the previous year, an increase of £3,187 19s. 2d. There has been a slight re-arrangement of this year's Accounts of the entrance fees and vellum diploma fees; the latter have been taken out of the heading of Building Fund and brought in with entrance fees. The life compositions show an increase of £277 4s., namely, £321 6s. as against £44 2s. a year ago, and as was also to be expected, in view of the larger sums invested, the dividends on investments have gone up and stand now at £1,357 14s. 4d. as against £993 13s. in the previous account, an increase of £364 1s. 4d. Another pleasing increase is the rent from tenants, viz. £6,240 5s. as against £5,865 10s., an increase of £374 15s. This is due to the fact that the upper floors of our premises on the Embankment have been advantageously re-let at an increased rent. The net rental from our Tothill-street property has also improved from £369 15s. 10d. to £529 14s. 4d., an increase of £159 18s. 6d., due to the smaller expenditure which we had to incur there.

"*Balance Sheet.*—Turning now to the Balance Sheet, on the liabilities side a change in the form of the accounts has been introduced and the item of Building Fund which has for several years past been found at the head of the liabilities has now been merged into the General Fund. This was the result of a meeting with the auditors, who have approved the arrangement. Consequently, the first item this year is Economic Life Assurance Society which last year stood at £31,074 3s. 5d., and is reduced to £30,198 5s. 5d. by £875 18s., the amount of the obligatory annual re-payment to the Assurance Society. The mortgage on the Tothill-street property of course stands as before. The Trust Funds Capital Account stands at a higher figure, generally due to the fact that the Paul Scholarship of £500 now appears for the first time, and the invested income of the Wilde Benevolent Fund shown separately last year as £640 14s. 8d. has now been brought in under this head, increasing it to £2,586 19s. 2d., including an additional investment in 1919 of £100. The Reserve Fund (mortgage redemption and contingencies) which last year stood at £8,000 now stands at £11,000, an increase of £3,000. The General Fund, as already mentioned, is now augmented by the amount formerly standing to the debit of the Building Fund and now stands at £80,834 12s. 8d. On the assets side the amount of the Institution building and lease is shown as £70,068 18s. 6d. as against £70,346 10s. 8d., the difference, viz. £277 12s. 2d., being the amounts of the two premiums paid during the year in respect of the policies of redemption which have been taken out to secure the principal sum of £75,000 at the termination of the lease of the Institution Building in 1984. I regret to think that there is no possibility of your Treasurer of to-day being able to tender you any assistance in realizing those sums at the due date. The only other item I need call attention to is the General and Reserve Funds investments. Last year these stood at £19,985 1s. 7d., whereas this year they amount to £26,985 1s. 7d., an increase of £7,000, which must be regarded as a matter for gratification. To prevent members of the Institution being unduly elated in this regard I may remind them that these investments have suffered considerable depreciation. For this reason among others it is very undesirable that any future deficiency in revenue should be taken out of reserve.

"In conclusion I desire to call the attention of members to paragraph (11) in the Council's Report on page 311:—'Practically all expenses of administration and the cost of everything that the Institution has to buy have shown a considerable advance since the Institution was in its own home; and when it returns to adequate accommodation and full activities, it is more than probable that the revenue will fall short of the actual requirements, notwithstanding the exercise of the strictest economy. If the activities of the Institution are to be maintained and extended some increase in the subscriptions may have to be proposed.'"

The resolution was seconded by Major A. E. Levin, and after the Honorary Treasurer had replied to questions by Mr. W. C. P. Tapper and Professor J. T. MacGregor-Morris, the resolution was put to the meeting and unanimously adopted.

The following resolution, moved by Dr. W. H. Eccles and seconded by Professor J. T. MacGregor-Morris, was carried unanimously: "That the best thanks of the Institution be and are hereby accorded to the Council of the Institution of Civil Engineers for the kind hospitality extended by them to the Institution in placing their meeting rooms and library at its disposal."

Mr. Ll. B. Atkinson then moved: "That the best thanks of the Institution be accorded to the following officers for their valuable services during the past year: (*a*) the Honorary Secretaries of the Territorial Centres and the Local Honorary Secretaries and Treasurers abroad; (*b*) the Honorary Treasurer, Sir James Devonshire, K.B.E., and (*c*) the Honorary Solicitors, Messrs. Bristows, Cooke & Carpmael."

The resolution, having been seconded by Mr. W. M. Selvey, was unanimously adopted.

Mr. A. F. Harmer moved: "That Messrs. Allen, Attfield and Co. be appointed Auditors for the year 1920–21."

The resolution was seconded by Mr. P. S. Pitt and carried unanimously.

The meeting terminated at 7 p.m.

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NOTE ON THE THERMAL EFFICIENCY OF THE GENERATION AND USE OF GAS AND ELECTRICITY.

By Sir DUGALD CLERK, K.B.E., D.Sc., F.R.S.

Paper received 29 May, 1920, and read before THE INSTITUTION *10 June 1920.*

On March 19th, 1919, I read a Paper entitled "Distribution of Heat, Light, and Motive Power by Gas and Electricity" at the Royal Society of Arts.

In conjunction with Professor Arthur Smithells, C.M.G., F.R.S., and Professor J. W. Cobb, C.B.E., B.Sc., I prepared a Report addressed to the President of the Institution of Gas Engineers who then was Mr. Samuel Glover. The Report was entitled "On the Coal-Gas and Electrical Supply Industries of the United Kingdom." This Report was communicated to the President of the Institution of Gas Engineers on April 14th, 1919, and published immediately thereafter.

As a good deal of somewhat irregular discussion dealing with these two documents has appeared in the electrical Press, in a note to the *Gas Journal* dated February 10th, 1920, I stated: "It would give me great pleasure to discuss my Royal Society of Arts Paper and the Report by Professors Smithells, Cobb and myself at the Institution of Electrical Engineers, where I could meet competent electricians in a friendly debate. The question of the future efficiency, both for gas and electricity, could then be debated in a fair and honourable way."

In response to my request your distinguished President, Mr. Roger T. Smith, invited me to meet Mr. Wordingham and himself in order to decide upon the feasibility of such a meeting. Your President, I am pleased to say, agreed with me as to the desirability of a debate with the Institution of Electrical Engineers.

I have great pleasure in opening that debate, as arranged, with a short statement of the matters raised in these documents as to the relative efficiencies of gas and electricity.

Both Paper and Report discuss fully the thermal efficiencies of generation and distribution of gas and electricity, and also the thermal efficiencies of use of gas and electricity by various appliances when distributed.

The general conclusions arrived at by Professors Smithells and Cobb and myself as to generation and distribution are summarized under the heading "General Conclusions," Section 49 of the Report (see page 3 herewith). Both the present efficiencies and the future efficiencies for generation and distribution of Gas and Electricity are dealt with under nine heads.

In the body of the Report details are given of the efficiency of use for the production of light, for domestic heating, for industrial heating, and for the production of motive power. This side is also treated of in the Paper.

In order to show in a condensed form the relative thermal efficiencies of gas and electricity in generation, distribution and use for heat, power, and light, I prepared the Table annexed (see page 2) which deals with the values for the present average results for gas and electricity in the United Kingdom. The Table shows clearly the various steps, and in these steps it will be noticed that the average efficiency of use for gas and electricity, that is, the proportion of the energy of the gas or electricity delivered converted into useful work, is 42 per cent for gas and 59 per cent for electricity. The final results show that for heat production:

$$\frac{\text{Utilized heat units by gas}}{\text{Utilized heat units by electricity}} = \frac{18\cdot3}{4\cdot5} = 4 \text{ (approx.)}$$

for power:

$$\frac{\text{Utilized heat units by gas}}{\text{Utilized heat units by electricity}} = \frac{10\cdot9}{6\cdot8} = 1\cdot6$$

and for light:

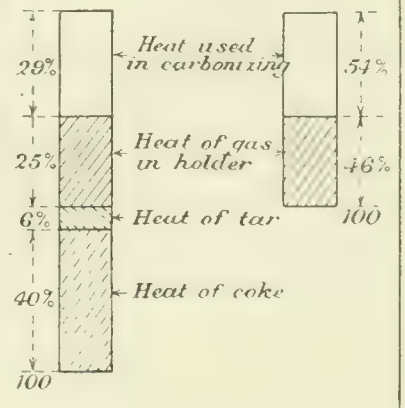
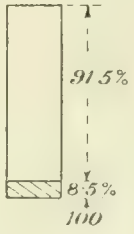
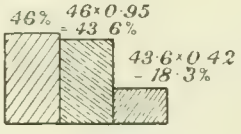
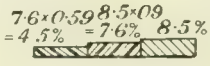
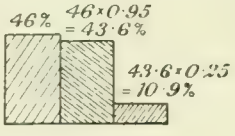
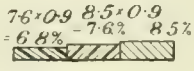
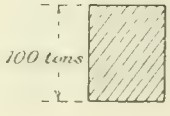
$$\frac{\text{Candle-power hours produced by gas}}{\text{Candle-power hours produced by electricity}} = \frac{203}{241} = 0\cdot84$$

These are the ultimate relative efficiencies.

From this it will be seen that the ultimate efficiency of gas for heating is very much greater than that of

TABLE.

THERMAL EFFICIENCY OF PRODUCTION, DISTRIBUTION, AND USE OF GAS AND ELECTRICITY FOR YEAR 1918.

GAS	ELECTRICITY	COMPARISONS
		HEAT CONTENT OF GAS. / HEAT EQUIVALENT OF ELECTRICAL ENERGY. $= \frac{4\cdot6}{8\cdot5} = 5\cdot4$
	HEAT. 	UTILIZED HEAT UNITS BY GAS. / " " " " ELECTRICITY. $= \frac{18\cdot3}{4\cdot5} = 4\ (Approximately)$
	POWER. 	UTILIZED HEAT UNITS BY GAS. / " " " " ELECTRICITY. $= \frac{10\cdot9}{6\cdot8} = 1\cdot6$
 Candle-Power hours produced by the consumption of 1 LB. of 13,000 B. Th. U. Coal at the Gas Works.	LIGHT 241 *Candle-Power hours produced by the consumption of 1 LB of 13,000 B Th U Coal at the Generating Station*	C P HOURS PRODUCED BY GAS. / " " " " ELECTRICITY. $= \frac{203}{241} = 0\ 84$
COAL CONSUMPTION FOR EQUAL PERFORMANCE. 		*To supply Electrically the number of useful Heat Units, Horse-Power Hours, and Candle-Power Hours at present furnished by the Gas Industry for every 100 Tons of coal used in Gas Making 265 Tons would be required at the Electricity Generating Station* COAL CONSUMPTION AT GAS WORKS. / " " " GENERATING STATION. $= \frac{100}{265} = 0\cdot377$

electricity; for producing motive power the efficiency is considerably greater by gas than by electricity; and for producing light there is a small advantage in favour of electricity.

The values for the future gas production and use are fully discussed in the Paper and the Report.

The general conclusions of Paper and Report are that an electric service of heat, light, and motive power in the proportion at present supplied by gas would increase the fuel consumption of the country for the same supply to over $2\frac{1}{2}$ times that required by the gasworks.

Comparing in the same way the efficiencies likely to be obtained in the future it is found that gas will still have a large advantage in a general system distributing heat, power and light.

EXTRACT FROM THE REPORT ON THE COAL-GAS AND ELECTRICAL SUPPLY INDUSTRIES OF THE UNITED KINGDOM, TO THE PRESIDENT OF THE INSTITUTION OF GAS ENGINEERS.

General Conclusions.

49. (1) At present the gasworks of the United Kingdom carbonize 20 million tons of coal per annum, producing towns gas, coke, tar and other by-products, with a thermal efficiency of from 70 to 80 per cent. Even regarding gas as the only useful product and after allowing for transmission and all other losses, the consumer receives as inflammable gas at least 45 per cent of the heat value of the coal which has been used at the gasworks to produce and distribute it.

Out of every 100 heat units in the coal used at the gasworks, 55 are reckoned as lost in the process of gas-making and distribution and 45 are available for the use of the consumer.

(2) At present, the electricity generating stations of the United Kingdom, including electric railways, deliver 7·6 per cent of the heat of combustion to the consumer. The boiler loss, turbine loss, thermodynamic conversion of heat into work and transmission loss account for over 92·0 per cent of the total heat.

Out of every 100 heat units produced by combustion in the central station boiler furnaces, 92 are lost as above described and only 7·6 are available for the purposes of the consumer.

(3) *Gas thus distributes* 45 *units of heat out of* 100 *at the gasworks, instead of* 7·6 *units of heat out of* 100 *consumed at the central station to produce electricity.*

(4) At present the best existing electricity generating undertaking in the United Kingdom delivers 12 per cent to the consumer and loses 88·0 per cent.

Electricians promise for the future super-stations a delivery of 17·6 per cent. Here the loss is 82·4 per cent.

(5) At present the best existing gas practice in the United Kingdom delivers about 53 per cent of the heat in the coal used at the gasworks to produce it and only loses 47 per cent in the work of generation and distribution to the consumer.

In the early future, all gasworks could distribute as gas to the consumer one-half of the whole heat of the coal carbonized, leaving $33\frac{1}{3}$ per cent of the whole heat in the unused coke and tar, thus realizing the high thermal efficiency of 75 per cent in the gasification process.

(6) *Thus, in the future, gas might be expected to deliver* 75 *heat units out of every* 100 *as compared with the* 17·6 *to be delivered by the prospective electricity super-station.*

(7) Except where temperatures above 1,700° C. are required, electricity, even in the future, is extremely wasteful of fuel, when applied to supply heat. Gas is many times superior in the great mass of heating operations.

(8) For lighting and power production, electricity in the future promises results which compare more favourably with gas, but even here the higher efficiency of the gas engine as compared with the steam engine, the future economies in sight in the production of gas, and its use with incandescent mantles render any monopoly claims of the electrical industries quite unjustifiable.

(9) Electricity is an efficient and convenient means of transmitting power and producing light. It is indispensable for electric railways, for transmitting power within works. It is required for many high temperature electro-chemical processes and for all electrolytic processes, so that it fills an increasingly important field.

It is an error, however, to suppose that electricity can economically displace gas for heat, light and power.

Discussion before The Institution, 16 June, 1920.

The President (Mr. R. T. Smith): I am very glad that this Institution has an opportunity of welcoming Sir Dugald Clerk, Professor J. W. Cobb and Professor Arthur Smithells, all of whom have been associated in the Report to the Institution of Gas Engineers, and Sir Dugald Clerk also read a paper before the Royal Society of Arts last March. Certain rather acrimonious criticisms of Sir Dugald's paper have appeared in the

correspondence columns of the technical Press, and Sir Dugald has been anxious to put the discussion on this question on rather a different basis. The Institution of Electrical Engineers, equally anxious that the discussion should be raised to a higher plane, decided to invite our friends to meet us here, firstly to see if we agreed about the facts, and, if not, to see if it were possible to say what facts are agreed and what are not agreed. I think, however, that we are meeting chiefly to emphasize the fact that we are all engineers or scientific workers engaged in the discovery of facts and in their discussion, and that we desire to understand each other's point of view. Although the deductions that we make from these facts may be different, it is largely for that reason we want to be agreed on the facts themselves. I shall ask Sir Dugald Clerk to open the discussion and to explain his " Note " (see page 765).

Sir Dugald Clerk : In connection with my " Note on the Thermal Efficiency of the Generation and Use of Gas and Electricity," I want to be quite fair to electricity, and I have always mentioned in the different papers I have written on gas and electricity that there are great advantages in the electric motor. The effect is, that although we have a very large number of gas engines in use in the country—over 1,000,000 h.p.—yet a great many people prefer electric motors ; in fact, so much is this the case that a visit to any large gas-engine works will show that whilst there is a central station generating electricity in every large gas-engine works, the cranes are all electrically driven and electric motors are used in other ways. Even in my own laboratory I had for many years a gas engine for my experimental work and an electric motor with it. Those people who have said I wished to stop the progress of electricity are under a misapprehension. Nothing is further from my mind ; I welcome the progress of electricity. I have studied its principles and have dealt with electrical matters from the beginning of the industry. The first time a gas engine was used to produce electric light in Scotland was when one of my engines drove a dynamo in Lord Kelvin's laboratory at the University. It is therefore apparent that I am not entirely ignorant of electricity, although I am not a professional electrician. There is a great and increasing demand for electric motors, and there are some purposes for which gas engines cannot compete with the electric motor, such as the supply of electric railways and tramways and, to a large extent, smaller power transmission applications ; people naturally use the electric motor because it is so easy to start. Whenever it comes to providing for a uniform heavy load such as a factory requires, the gas engineers compete favourably with the electric engineers at present efficiencies of power distribution. Some electrical writers have imputed most mysterious motives to me, but they forget I am the oldest gas-engine designer in Britain —in fact the only pioneer left. I have always considered the interests of gas as of great importance to the country, and I do not wish to see it superseded. It will be remembered that in the Report of the Coal Conservation Sub-Committee certain estimates were made. The Sub-Committee thought that by utilizing electricity for power and heat and dispensing with the whole of the present steam power services about 55 million tons of coal a year could be saved. I came to the conclusion that that was not correct. I do not know how the Sub-Committee fell into the error, but they certainly had an inadequate idea of the thermal efficiency of the modern gas-works, and I felt bound to go into that matter because it was a very serious thing for the country and the gas industry. At that time Members of Parliament were all talking as if the gas industry were dying ; but it was not, it was an industry with a capital of £200,000,000 and growing rapidly. It was my purpose to show the real facts about the industry. I have compared the efficiencies likely to be obtained in the future, and I found that gas will have a large advantage in a system distributing heat, power, and light. So far as heat is concerned gas would still maintain its advantage. The column headed " Gas " in the table in my " Note " shows a diagram divided into four sections of 40, 6, 25 and 29 per cent respectively. The 29 per cent at the top represents the heat used in the carbonizing process, the 25 per cent next is the heat of the gas transferred on the average to the holder in Great Britain, 6 per cent is the heat found in the tar, and 40 per cent is the heat in the coke. To determine thermal efficiency I have assumed that the 40 per cent of the coke and the 6 per cent of the tar are still available ; they are quite as available for heating purposes as the original coal, because coke is very largely used for boilers and for many other purposes, and also has a great use in connection with gas producers for gas engines. I consider the heat the coke and tar could give out is heat which is still conserved from a ton of coal ; that is, 46 per cent is reserved from the ton of coal for use in another way. Again, I have calculated the efficiency of gas production by debiting the production of gas with the whole heat expended in the whole carbonizing process. The efficiency of carbonization is about 71 per cent, but the actual efficiency of the gas-production process is 46 per cent, so that out of 100 heat units used to produce gas, assuming coke and tar be not debited with any heat of carbonization, but that the whole of the heat lost is used to produce the gas, 46 per cent of that heat is in the form of gas in the holder and 54 per cent has been used for gas-producing purposes. In the next division of column I have taken that 46 per cent and multiplied it by 0·95, which is the efficiency of transmission. The efficiency of generation in the holder is 46 per cent, but that multiplied by 0·95 gives 43·6, which is the actual heat obtained by the user. There is also a smaller block, which shows 43·6 multiplied by 0·42, which is equivalent to 18·3 per cent. The ultimate efficiency in use, 42 per cent, is the efficiency of use of gas in the average consumer's appliances. Supposing 100 heat units of gas were supplied to the average service of cookers, water-boilers, and incandescent gas fires, 42 per cent would be returned in the form of average work. The ultimate efficiency of the whole process is 18·3 per cent in the actual use of the apparatus. Similarly with electricity (second column), the 91·5 per cent is the heat of thermodynamic transformation, and the 8·5 per cent is the actual heat equivalent of the current generated at the central

station. That is the average in Great Britain in 1918, according to the Coal Controller's figures. In the third column I have made comparisons of the actual heat generated, and it will be found that the ratio is 46/8·5, or 5·4 times in favour of gas. In the next division of the second column the heat to be obtained from electricity is taken to be 8·5, which, multiplied by 0·9 for the losses due to transmission, gives 7·6. From this figure, in the same way as I did with gas, I found the efficiency of use throughout the country in electrical heating appliances to be 59 per cent, and the ultimate heating efficiency is 4·5 per cent. To obtain a really accurate figure it would be necessary to get a census both of use and consumption throughout the whole of the United Kingdom—a great undertaking but a very desirable one. With power the same operation has been gone through, and the ultimate result is that the ratio of heat units utilized by gas to those utilized by electricity is 1·6, with the figures as they are at present. With light we have to use a different method, because we cannot get it in terms of thermal efficiency. The candle-power-hours produced by the consumption of 1 lb. of coal of 13,000 therms at the gas-works would be 203. For the same consumption of coal at the electricity generating station, as far as I can make out from the figures I have got, the figure would be 241. That is to say, electric lighting shows a superiority in thermal efficiency, but that superiority depends on certain assumptions which I have had to make as to the proportion of half-watt lamps and 1-watt lamps and the average current they took. These matters are all discussed in the main Report. I took the general result because I wanted to show the contrast between the conclusions of the Government Committee on Coal Conservation and my own. Consider the present service of heat, light, and power by the gas-works of the United Kingdom to be superseded by electricity generating stations, then it would be found that, for the same heat, light and power service, the coal consumption would be 265 tons instead of 100 tons for equal performance. That is the present state of affairs. With regard to the future, of course there is the hope of getting an efficiency of electric generation at the station of 20 per cent, and I believe in some cases it has gone up as high as 16 or even more. I studied this question last year, when I went to Newcastle-on-Tyne to read a paper on the thermal efficiency of different types of engines, and I took the opportunity of investigating the possibilities of the internal combustion engine—that is to say, the limiting efficiencies we could hope for with any immediate development—with Sir Charles Parsons, and he discussed the limiting efficiencies obtainable in the turbine. I stated that we hoped for a 46 per cent efficiency with gas motors, and Sir Charles thought he could obtain 28 per cent with his latest steam turbines, but the conditions in both cases were quite exceptional. However, it showed that it would be very dangerous to interfere with the development of two great industries like the steam turbine and the internal combustion engine while there were possibilities of that kind, because if the Coal Conservation Sub-Committee had any idea of such figures both their own figures and their outlook would have been different.

Mr. C. H. Wordingham: For many years I have consistently advocated that gas and electrical engineers should join hands for the common good instead of regarding one another as rivals. I have been equally criticized by my colleagues and by those whom I ventured some time ago to call "our friends the enemy," but I am all the more convinced that combination is the proper attitude to adopt. Sir Dugald Clerk has put forward a number of figures which will no doubt raise a great deal of controversy. When I saw his challenge in the *Gas Journal* I felt that it ought to be accepted, not only because if it were not accepted it would be construed as an admission on the part of electrical engineers that the figures were correct, but also because I believe all of us really want to get at the facts, which can best be done by approaching the matter in a scientific spirit and by freely discussing what those facts are. I should like to make a few general observations on the whole subject. Sir Dugald has said, with reason, that electricity is not a source of energy. It is, in effect, a gearing placed between the fuel and the consuming devices which have to utilize the energies of the fuel, and as a gearing it will have to be judged not only by its efficiency but also by its convenience and adaptability. Not only is electricity convenient, but its very convenience means that the economy of heat in its use is much higher than would appear from the figures given by Sir Dugald. The adaptability of electric motors and electric heating and lighting is such that the same work can be performed with a smaller expenditure of energy, because economies are possible with electric working that are impossible with gas working. A motor may be switched on, for example, as often as desired, but to stop a gas engine and start it up again requires consideration. When a gas engine is running light it is running very uneconomically. I want to emphasize this adaptability of electrical energy because I think it is of the greatest possible importance. The controversy between advocates of gas and electricity reminds me very much of the controversies about food values. The average man, whatever the theoretical arguments may be, always prefers English roast beef to beans, and asparagus to cabbages. I think electricity is the roast beef and asparagus, and the cabbages and beans are represented by gas. I have no doubt that there is an enormous amount of nourishment in a piece of wood, but very few of us would like to try to extract it. Let us for a moment admit all the figures. It seems to me that, even then, gas could be very much better applied to drive electric generators than be supplied to the consumer in its crude form. In this country large gas engines are, I think, very much under a cloud, perhaps because they are very largely built to German designs; but I hope that British designs will in the near future make their appearance, and if those limiting efficiencies which Sir Dugald has mentioned, towards which designers should work, are in fact realized, then we get the advantages of the economy in the gas engine combined with the advantages of electric gearing, and this, I believe, will lead to increased efficiency.

Professor J. W. Cobb: Proposals regarding the

distribution of the energy of coal by means of electricity have been made recently. They are of a very drastic nature from the standpoint either of the electrical industry or of the gas industry, and are made in the name of coal conservation. They raise the whole question of what is the best method of liberating and distributing the energy of coal. Sir Dugald Clerk's statement summarizes, in very precise and simple terms, what the position was when he, Professor Smithells and I, investigated the matter. In any scheme for utilizing the energy of coal we are concerned with processes of transformation and inevitable loss, and a scheme will be good from the point of view of fuel economy to the extent that these transformation losses are minimized. Now one of the most inefficient processes we know for the transformation of energy from one form to another is the extensive conversion of heat units into motive power. This inefficient process of transforming heat into power is a necessity so long as we are concerned with power alone. If the loss is not incurred at a central station, it has to be incurred somewhere else, and is in that case usually much heavier. For that and other reasons the electrical power station is increasing its hold on the industrial public as far as the supply of power is concerned and no one could have anything but praise for its continuing development. When the energy is wanted by the consumer for any purpose other than power, the conditions are completely altered. It is no longer necessary to burden a system with the 80 or 90 per cent initial waste in the power station, which no economy in use can counteract. To take the power station for the supply of energy in general is to load up all the processes in use with the necessary inefficiency attaching to the generation of power. That is not the high road to fuel economy. The gas industry seemed to have been rather overlooked in this matter and an assertion of its position was necessary. It had undoubtedly come to be regarded by many as an old-fashioned and inefficient industry. There was a limited measure of truth in this view. Technical developments in the gas industry had, undoubtedly, been delayed by the extent to which it was governed by statutory regulations. These were imposed when gas was used almost exclusively for lighting and before it was extensively used for heating and power. These restrictions had outlived their usefulness; their cramping influence survived. There is a moral in that for any industry. The legislative changes which are now being made on the advice of Sir George Beilby and the Fuel Research Board, offer a new liberty to the gas industry. The accusation of inefficiency in the gas industry was never justified. The process of carbonization, even as it is carried out in the older established plant of the country in horizontal retorts, is by no means inefficient; all the products are valuable, and the by-products are essential to any civilized nation. I wish to call attention to the extent to which the figures given are based not upon what can be done in reconstructed plants, but on what is being done at the present time throughout the country. The efficiency at the gas works is so high, and the losses on distribution so small, compared with the corresponding figures for electricity, that for most purposes a very handsome margin of economy remains with gas even when one takes into account the higher efficiency of some electrical appliances. As far as power is concerned we must not forget the high thermal efficiency of the gas engine, which might have been the standard prime mover to-day if it had not been for the splendid engineering skill which has created the steam turbine and made it the recognized unit for the generation of power on a large scale. The gas engine cannot be ignored. On the other hand it would, of course, be foolish to attempt to limit the claims of the electrical industry to power and lighting, on the assumption that it could never provide heat economically. There are processes in which the large initial loss in the generation of electricity can be counterbalanced by efficiency in use, but that is a very different thing from any wide claim to undertake heating operations in general, for which electricity is really very ill adapted. In the natural course of things, both the electrical industry and the gas industry will grow by demonstrating that they can do certain kinds of work efficiently and well. But there is neither need nor justification to make a hot-house plant of either, nor can either industry be said to be in such a stage of development that it is advisable to stereotype throughout the country its present method and equipment. To put down very large stations and works, all of very much the same type and representing the same degree of development, would lock up an enormous amount of capital and incur a grave danger of hindering progress for many years to come. The position as regards fuel economy of the most modern power station is known to be very unsatisfactory. Technical literature of the last few years shows that the minds of the leaders in electrical matters are alive to this shortcoming and are prospecting all round, actively desiring improvement. The same may be said of the gas industry, which is examining its technical possibilities. I will mention in illustration just one in which I have been personally interested. To-morrow night in this room Professor McLennan is going to lecture on the production of helium. During the war the work on the recovery of helium seems to have established the probability of much cheaper methods for the production of oxygen, and my colleague, Mr. Hodsman, and I have calculated that if oxygen were so far lowered in price that it could be used in a continuous gasification process, then complete gasification could be effected with an efficiency of gas production of 90 per cent. Supposing that could be done, and there is nothing inherently impossible, or even improbable, about it, the consumer could be supplied with a gaseous fuel in the production of which only 10 per cent of the original heat of the coal had been lost. To sum up, no one can foresee what the developments of the electrical industry or gas industry are going to be. The primary need of each is a complete freedom to develop according to its own needs and proved capacities for public service.

Mr. C. H. Merz: As I was Vice-Chairman of the Sub-Committee that drew up the so-called Coal Conservation Report, I ought perhaps to deal with one or two questions referred to therein which have been mentioned by Sir Dugald Clerk, and also generally deal with some of the matters raised there. First of all I should like to point out that the primary object of the

Report was to deal with economy of fuel in the production of motive power. There were, I believe, some references in footnotes to the use of electricity for heating, but it cannot be said that the Report dealt with that question. Sir Dugald and his colleagues immediately took the whole Report and referred to it as if it dealt with heat energy. I do not think there is anything on the question of the economy of fuel to be derived from an improved distribution of energy in a form available for motive power that I should wish to alter, and I should be surprised, although I have not consulted them, if my colleagues on the Sub-Committee differed from me in what I have said. The whole question was dealt with from the point of view of the production of motive power, and great care was taken to separate out the fuel (coal) used for heating purposes in industry. The next question I might mention, although possibly it has been corrected, is the general criticism that the Coal Conservation Sub-Committee's Report recommended the setting-up of 16 large super-stations to supply the whole country. There is nothing of that kind in the Coal Conservation Report. All the Coal Conservation Report suggested and recommended was that this country, for the purposes of standardization, periodicity, and so on, should, in order that power might be collected where available and distributed to where it was used, be divided into some 16 electrical districts. That general policy has been approved, and the chief recommendation of the Coal Conservation Report—that Electricity Commissioners should be appointed to deal with that matter—has received the support of the Government. I believe that the electrical industry is, generally speaking, very well satisfied with what has been done, and is now chiefly anxious to be let alone, and that the Commissioners should be allowed to carry out their policy. I should like most emphatically to point out that I am sure nobody on the Coal Conservation Sub-Committee ever dreamed of one station supplying each of those 16 areas; it clearly would not be economical to do so—it would be uneconomical from a distribution point of view. The only possible cases in which the direction of extreme centralization of that kind might be followed, would be where there was shortage of water facilities; otherwise it is quite clear that energy would be collected into the main distribution system from points where it could be obtained most cheaply. Another question which has been repeatedly referred to is that of the efficiency to be expected from modern electric power stations. Values of 17 and 18 per cent have been named as possible figures in the future, and therefore it is perhaps desirable to say that those figures are being daily obtained in various stations in this country and in America and, what is more important, they are being obtained with the use of very inferior fuel. The figures in the Coal Conservation Report were conservative in that they were based on a comparatively high quality of fuel. The reason was that the fuel in question was that in general use throughout the country. Small users who generate their own power to-day generally choose a comparatively high quality of fuel, as it has to be used in Lancashire boilers. If the quality of the fuel for the purpose of the central station were taken at anything like the quality which was put down for the purpose of calculation in the Coal Conservation Report, the efficiencies would be very much higher than are being obtained to-day, i.e. higher than 18 per cent. I will not speak further on the future, except to say that the chief complaint of electrical engineers is that they have not, except in one or two individual cases, had the opportunity, in this country at any rate, of developing and using large units of motive power for the purpose of their central stations. Parliamentary legislation has prevented that. The author has taken thermal efficiency as the basis of his calculations. As the Coal Conservation Sub-Committee also dealt with the matter from the fuel point of view I do not know that one can quarrel with a reference to it being made, but it is very necessary to point out, as Mr. Wordingham has already done, that this is not by any means the whole question, which really is: How can we use labour to the best advantage? For practical purposes, coal is only labour. Of course I know there are royalty holders and so on who are accused of taking a good deal of the profit, but we know it has been well brought out in all the inquiries that, practically speaking, coal is labour. Industrial processes are labour. In the average industrial establishment it will probably be found that motive power represents, even at to-day's prices, from 5 to 10 per cent of its labour bill. It is quite clear that a man who is running an industry has to consider how he can save money and produce his product more cheaply. The chief thing he has to save is his labour, i.e. 90 per cent of the total cost, and he must therefore have his motive power in the most available form. Thus it is impossible to expect improvement in coal conservation by distributing something which, from the point of view of motive power, is not what the manufacturer wants. The question of how far it is possible to argue the whole case on a purely thermal basis, is one of the relative importance of saving labour in getting coal and in industry generally. That was very clearly put forward, in the Coal Conservation Report, and I think the more we consider the matter the more we shall see that that is the true point of view. Dr. Ferranti was, in fact, perfectly right when he said that electricity was the most useful medium, and that through electricity any energy for motive power could be most usefully and easily applied without waste. That is the interest of the manufacturer. If we go further into that side of the matter we shall realize, especially with the present tendency as regards cost of labour, that the important thing is that machines which do not automatically maintain their highest efficiencies, which require attention and adjustment and skill, should not be put into the hands of the man in the factory or the woman in the house. We want a machine which will run automatically, and that is a feature of the electric motor which maintains its efficiency without attention. The author has referred to gas engines on test as having efficiencies of from 20 to 25 per cent at various loads, but anyone who has replaced gas engines by electric motors knows that those efficiencies are not obtained except under very exceptional circumstances. At least, if these figures represent the efficiency of the gas engine, I can only say that in a very large number of cases the efficiency of the electric motor

which replaced it must be 200 per cent! I may once more refer to a question in connection with motive power which our gas friends have to answer, viz. that a very large percentage of all recent factories have not only employed electricity, but have used the public supply. It is the older factories which retain other forms of motive power. In connection with this whole question the enormous amount of power that is used in the country districts, where no gas is available, must not be forgotten. It was that power which was very largely responsible for the savings estimated, and which I believe will still be attained by the policy proposed in the Coal Conservation Report. The Report did not suggest that the gas industry should disappear; it did not propose to displace it, and it did not attack the gas industry at all. There are statistics of what has happened in other places where electricity has been greatly developed (notably Chicago, with which I am connected in an advisory capacity, and which is one of the places where electricity has been developed more highly than anywhere else) which show that the gas industry has not suffered. I do not think that anybody, in preparing the Coal Conservation Report, proposed that anything should be done to discourage the use of gas; in fact, it is to the interest of electrical engineers to encourage the gas industry as much as they can. The gas industry, as regards its improvement, is a question of the carbonization of coal and the improvement of the gas engine, or of the internal combustion engine, or the gas turbine, if such be possible. The more these things are developed the better for the electrical engineer. Those who speak for electricity, I think, believe that it will steadily progress as a distributing agent, and if that is so we cannot wish for anything better than improved systems of power generation, which may be obtained, possibly, through the medium of gas. These improvements cannot be so obtained at present, except in special cases. I have figures of some of the largest gas stations in the world, where accurate figures are kept as to the output in a way that can be measured, and most of these large stations have not got efficiencies as high as the figures I have mentioned for the best electric stations. I shall be very glad if Sir Dugald Clerk can produce figures to the contrary, but of course they must be figures based not on the estimated h.p.-hours or estimated unit output, but on the actual metered units. I should be very much interested to know if such figures could be given. The gas industry is in somewhat of a dilemma. For the moment, we have a triple alliance in which the distribution side of the industry has joined hands with the engineering and producing sides, but they have still to decide whether they want to aim at an extension of the direct use of gas for motive power in factories or whether they will cater for the electrical engineer and supply him with heat units. They have not yet got to that point but I hope they will do so. I shall certainly be very glad to discuss the purchase of heat units by any concern with which I am connected. We should like to obviate the use of raw coal. They have not done that, and I do not think, in spite of their claims for efficiency on the heat side, they can do it, but I hope they will develop their business from that point of view. I should like to close on the same note that Mr. Wordingham did, and to say that we electrical engineers wish that the two industries should be developed together. Between them they can certainly do an enormous amount to improve the efficiency of labour and to reduce the onerous part of it.

Mr. J. S. Highfield: I cannot imagine in connection with two industries which in a large measure serve the public in similar ways anything more desirable than that they should understand each other's point of view, and I am proud to think that I am one of the few electrical engineers who have made a contract for street lighting jointly with one of the largest gas companies. If the thermal efficiencies given in the paper—which I am not questioning except in one respect—were the determining factor in settling whether electricity rather than gas should be supplied it is perfectly evident that, except for light, electricity would be supplied for neither power nor heat. Having regard to the fact that the gas industry started a great many years before the electrical industry, and that electricity worked its way up from small supplies of light until it is one of immense magnitude, supplying power and heat, it is quite clear that, assuming the correctness of the figures, thermal efficiency is not the determining factor. I would also say that the theoretical cost is not the determining factor. If efficiencies of 100 per cent be assumed, and the cost of electricity, gas and coal be taken as being 1½d. per unit, 4s. per 1,000 c.ft. and 40s. per ton respectively; at a cost of 1d. with electricity 2·36 lb. of water can be evaporated from and at boiling point; with gas, 12·9 lb.; and with coal, from 60 to 70 lb., according to its calorific value, so that cost is not the determining factor, otherwise no gas would be sold. I am interested also to note that Sir Dugald Clerk in all his illustrations contemplates the replacement of gas by electricity in spite of his calculations showing that this would increase the expenditure on coal. I do not think he gives a single example of the reverse process, i.e. the substitution of gas for electricity. To scrap all the gas-works in the country and replace the gas supply by electricity supply is altogether out of the question. The works will exist and will continue to grow, and it is to everybody's benefit that they should do so. I imagine that gas will have no chance at all for the supply of power over wide areas. The supply of power to very large motors for collieries and works of every description on the scale required would be impossible with gas or any other agent except electricity. On the other hand, for electrical engineers to try to supply all the cottages in a large town with power for electric cooking apparatus is probably equally impossible at the present time. Therefore it is clear there are certain fields where the two can serve most useful purposes. Where gas may help us very much, as Mr. Merz has indicated, is in showing better means of changing the heat energy of the coal into power. That is what everybody is seeking, and if the gas engineer can accomplish something towards that desirable end it would be of great benefit. This end would have been accomplished much more easily had it not been for the necessity of building plants of the very largest size. If they had been confined to units of from 2,000 to 3,000 h.p. I have not the least

doubt that the gas engine would have made great progress in power stations. What has made it impossible, or at any rate extremely difficult, is the fact that a unit of 3,000 k.w. is of very little use in the big power schemes we have to contemplate to-day.

Mr. C. P. Sparks: I endorse Mr. Merz's remarks with regard to the mis-statement in the paper relating to the number of super-stations proposed in the Coal Conservation Report. On reference to the recommendations, section (48) of the Report, sub-heading (1) clearly sets out that the existing 600 districts should be superseded by 16 districts. No mention is made of the number of power stations, which is a matter left to the decision of the Electricity Commissioners. In opening the discussion, Sir Dugald referred to the estimated saving of 55 million tons of coal per annum as including coal saved through supply of electricity for heating. Reference to the Report, section (1), sub-section (9), shows that the figure of 55 millions did not include coal used for heating purposes. Sir Dugald states in his Royal Society of Arts paper that the Sub-Committee suggest a coal consumption of 1 lb. per electrical h.p.-hour. Reference to Appendix "A" of the Report gives the basis of the estimated saving in section (1), sub-section (9), as being $1\frac{1}{2}$ lb. of coal per h.p.-hour. With coal of 13,000 therms, and with an efficiency of distribution of 85 per cent, the thermal efficiency of a power station to obtain the results suggested in the Report would require to be $17\frac{1}{4}$ per cent as compared with that of 19·6 per cent suggested by Sir Dugald. If the efficiency of distribution were as high as 90 per cent, as suggested by Sir Dugald, the thermal efficiency would be 16 per cent. The thermal efficiency implied in the Coal Conservation Report has already been reached when operating on a far smaller scale and with smaller turbo-alternators than the Report proposes. Since the date of the Report, improvements including use of increased steam pressure and temperature make it certain that a higher thermal efficiency will be obtained.

Comparison of gas and electric undertakings.—Sir Dugald suggests that a great economy in fuel could be secured if the general distribution of power, light and heat were carried out by gas in place of electricity. This economy would be obtained by contrasting the thermal efficiency of gas undertakings carbonizing some 20 million tons of coal in Great Britain which produce gas at the works with a thermal efficiency of 46 per cent, with certain steam electricity generating stations, using $6\frac{1}{2}$ million tons of coal, and operating with a thermal efficiency of 8·5 per cent. It is quite unfair to compare the average results of hundreds of small generating stations, many of which are unsuited to supply power on a commercial basis, with the result of well-established gas undertakings, and the only fair comparison is to compare undertakings operating under similar conditions as to magnitude and field of operation. If electric generation were being carried out on a scale approximating to the future demands, it would be impossible to adopt proposals on the lines set out in the Coal Conservation Report, but comparing the electric development in Great Britain with that in other countries it is clear we have only touched the fringe of possible development, and this is one of the main reasons that makes the gradual replacement of hundreds of small generating stations possible. I should like to point out that electrical engineers are not wedded to any particular source of energy; steam, gas, oil, or water can be used as the primary source of power to produce electricity which, after all, is only a convenient means of distributing energy. If gas were the flexible and efficient agent suggested by Sir Dugald, we should prefer its use in driving our power stations to the use of steam turbines, which are comparatively inefficient from a thermal point of view. While there is a possibility of large gas engines or gas turbines being produced, the experience of the last 20 years does not hold out any great hope of their development unless a new material is discovered which possesses high tensile strength at high temperatures. In spite of many attempts, we have been unable to use the gas engine on a large scale as a power producer. If we could, I agree that it would halve the fuel consumption at the power station as compared with the results at present obtained with steam turbines. Sir Dugald suggests, on page 13 of his Royal Society of Arts paper, that "the real competition between gas and electricity, from a point of view of coal conservation, arises in the field of illumination, and not in that of heating or motive power." Our friends in the gas industry should be aware that there is no direct competition between gas and electricity for power purposes, as gas in conjunction with the gas-engine is an unsuitable distributing agent for detail power requirements. If anyone requires confirmation of this statement, I suggest a visit to Pennsylvania, where he will find at least two large, prosperous electric power companies distributing electricity on a large scale, although they are in direct competition with natural gas, which is obtained at the lowest possible cost. If further confirmation is required, the relative horse-power put in use for power purposes by electric or gas drive during the last five years will supply the answer.

Power.—On page 13 of the Royal Society of Arts paper Sir Dugald states: "With regard to motive power under what may be termed the best gas works and electricity generating conditions, the gas engine gives a return of 13·6 per cent b.h.p. for 100 heat units used at the gas works, while electricity returns 10·4 per cent." The figures for gas were arrived at by taking the thermal efficiency of the gas engine operating at $\frac{3}{4}$ load to be 25 per cent. While such a figure may be obtained on test, it is not maintained in practice. Further, the average efficiency of gas plant operating on variable load is far lower than the figure suggested. It is again lowered by the difficulty of starting and stopping, the gas engine necessitating its being kept continuously in operation, whereas an electric motor can be shut down readily when employed on any intermittent process. The table attached to Sir Dugald's note which is before us to-night suggests that the thermal efficiency of an electric motor is 6·8 per cent. This is arrived at by taking the thermal efficiency of electric power stations at $8\frac{1}{2}$ per cent or 40,000 therms per kw.-hour, while the efficiency of transmission and of the motor are each taken at 90 per cent. The thermal efficiency of the best electricity generating conditions

(apart from such stations as are contemplated by the Coal Conservation Report) should be taken at 16 per cent, thus increasing the thermal efficiency per b.h.p. in the ratio of $6{\cdot}8 \times 16/8\frac{1}{2}$, i.e. 12·8 per cent. Comparison of this figure of 12·8 per cent with 13·6 per cent given by Sir Dugald, shows a thermal superiority for gas, on the basis he selected, of between 6 and 7 per cent, but having regard to the known inefficiency of gas engines when employed on variable load, the actual thermal efficiency is substantially in favour of electricity. To sum up, there is a substantial advantage, from the point of view of coal conservation, in using electricity for motive power in place of gas.

Lighting.—On page 20 of his Royal Society of Arts paper Sir Dugald suggests—assuming an equal number of inverted incandescent and vertical lamps for gas lighting at 64 therms per candle-power and one-watt electric lighting at 54 therms per candle-power—that electricity would require 84 per cent of the heat used by gas. The ratio in favour of electricity is of a much higher order.

Gas (page 17).—If coal is completely carbonized, the heat units available in gas per ton of coal of 13,000 therms are $65{\cdot}2/100 \times 29{,}200{,}000 = 18{,}900{,}000$ therms.

Candle-power-hours per ton available to consumers.—

(*a*) Upright type mantle .. 18,900,000/82 = 230,000
(*b*) Inverted-type mantle .. 18,900,000/47 = 402,500
(*c*) High-pressure burners (unsuitable for small units of light) .. .. 18,900,000/23 = 820,000

The above figures are subject to mantle renewals to maintain the figures of 47, 82, and 23.

Electric (page 7).—On the basis of 3·47 lb. of coal at 11,600 therms per kw.-hour, being the average of a number of electric generating stations—

Therms per kw.-hour = $3{\cdot}47 \times 11{,}600 = 40{,}200$
Kw.-hours per ton of coal = 725

Page 8—

Efficiency of distribution = 90 per cent
Kw.-hours per ton available to consumers = 650

Candle-power-hours per ton of coal.

(*a*) Metal filament lamps of small candle power (average life 1,000 hours) .. 540,000
(*b*) Half-watt type lamps of small candle power (average life 1,000 hours) .. 800,000
(*c*) Half-watt lamps of 1,000 candle-power and upwards 1,300,000

Taking the average of items (*a*) and (*b*) both for gas and electricity, the figures are—

Gas 310,
Electricity 670,

so that gas requires 2·15 times as much fuel as electricity for the same amount of light under the conditions defined, as compared with the ratio of 64/54 or 1·2 given by Sir Dugald on page 20. Apart altogether from the fuel saving through the use of electricity, the latter possesses the great advantage of non-contamination of the atmosphere, and, through the absence of heat and products of combustion, minimizes depreciation of internal decorations.

Heating.—Electricity does not compete directly with gas for heating. Gas is in direct competition with coal for industrial work, and the competition to replace the open coal fire lies between gas and the closed combustion stove. Electricity is used for special purposes where high temperature is required, for chemical purposes, and where the infrequent use of heating appliances makes its flexibility a convenience, or where low thermal efficiency at the power station is offset by the high efficiency of the detailed apparatus. I should be interested to hear from Sir Dugald as to the basis on which he prepared the table accompanying his note which suggests that the detail apparatus used for gas heating has a thermal efficiency of 42 per cent. Having regard to the large amount of heat carried away by the products of combustion, I should have thought that the thermal efficiency of this class of apparatus was substantially lower than the figure given. On the other hand, he suggests that the efficiency of detail apparatus for electric heating is 59 per cent. As electric heating is normally internal and there is no loss from products of combustion, I should have considered that the difference of efficiency would have been greater than the figures of 42 per cent and 59 per cent suggested.

Coal consumption for equal performance.—The author in his introductory Note claims that complete electric service in place of gas would increase the fuel consumption of the country—for the same supply—by over $2\frac{1}{2}$ times. This statement is primarily based upon electricity replacing gas for general heating; no such claim has ever been made by electrical engineers, and if this element is excluded from the balance sheet it will be found, subject to the criticisms made by me under the headings power and light respectively, that the balance sheets shows a substantial thermal saving in favour of electricity.

Future co-operation.—On page 23 of the paper Sir Dugald points out that the vast field for use of electricity is realized by gas engineers. We, on our side, realize that gas has its own special field. There is room for the fuller development of both these public utilities, and one would hope as an outcome of this discussion that the two industries would try to co-operate to a greater extent in the future than has been the case in the past. Having regard to the tables given on page 11 of the paper, it would appear from a thermal point of view that gas-works are really coke-works, as some 58 per cent of the original heat units remain in the coke and tar produced, only some $23\frac{1}{2}$ per cent of the thermal value of the coal leaving the works as gas. Any large increase in the present output of gas will result in a serious problem of coke disposal, and there should be some possibility of the gas undertakings supplying heat units to electricity undertakings for production of the most flexible agent for distribution of power. A further reason for co-operation between the two groups of undertakings is the making of the best use of all classes of coal. At present gas is mainly produced from a high-grade coal, many grades being at present entirely unsuitable for gas production. On the other hand,

electricity can be produced from any class of coal, but in this country is mainly produced from the lower grades unsuitable for gas making. Neither in the paper nor in the Note does Sir Dugald make any suggestion as to what would be done with coal unsuitable for gas manufacture.

Mr. W. H. Patchell: I think far too much has been made of this so-called attack on the gas industry. Sir Dugald Clerk says on page 23 of the reprint of his Royal Society of Arts paper that it would be a serious matter if engine development were hampered, and that legislation restricting the use of electricity as the one source of light, heat, and power would be fatal to the prosperity of the country. That may be an inference from the Report but I do not find it there. It aroused the attention of politicians when party politics were taboo. Electricity was to be the cure-all—" rivers of electricity " were to wash away the effects of the war if not the whole national debt. The Report told us (page 8 of Report, Cd. 9084) that " the pre-war earning power or wages of each individual was far too low." We have with us to-night the first and the last signatories to this Report and I think they will admit that high wages have meant the conservation of energy in another sense than the slogan of the Report. The Sub-Committee say on page 21, " Existing generating plants are uneconomical and ought to be scrapped." There is no qualification —they are all in that category; and they go on to say, " but this cannot be done until more modern plants are made available." The cure was that super-power stations were to be set up in 16 areas, and were to save 55 millions of the 80 millions of coal used for industry. How is that 80 million tons arrived at? On page 26 of the Report I find it is based on Mr. Flux's figure of $70\frac{1}{4}$ millions which the Committee says were figures 10 years old, and corrected them to 80 millions. The Report shows distinctly that Mr. Flux excludes from his table all the coal used for blast furnaces and also all the coal carbonized in gas-works. That simply proves how the 55 millions is arrived at. I do not find the 18 millions, or 20 million tons of coal as Sir Dugald Clerk puts it, that are carbonized in the gas industry, included in the 80 million tons laboured by the Report and touched by the saving suggested. It is primarily the politician and not the electrical industry that he should attack, if anyone, and there we ought to make common cause. High wages earned by scrapping all existing plants, by the output of super-power stations paid for as much as possible, to the tune of 25, or, as some people said, 150 millions sterling from the public purse was an attractive Parliamentary cry, especially with the liberal interpretation it got in the House of Commons. I submit that the relative positions of the electrical and gas industries are better shown in the recommendation made to the Committee by the most eminent gas engineer in this country, Dr. Charles Carpenter, who, giving evidence before a House of Lords Committee a few days ago, was of opinion that having regard to the competition of electricity the existing sliding scale ought to be abandoned. The thermal efficiency of gas-works is well known and improving. The thermal efficiency of a modern electricity generating station is also well known and Sir Dugald Clerk knows that it is much higher than the average figure given by Mr. David Wilson, which was based on all the stations in the country, old and new, on a low load factor. For purposes of comparison Sir Dugald should have taken 18 or 18·5 and not 8·5 per cent. On those figures I ought to point out that copies of Sir Dugald Clerk's paper on the " Distribution of Heat, Light, and Motive Power," reprinted from the *Journal of the Royal Society of Arts*, have been circulated, but the discussion which is included is only an abstract and there is an important figure omitted. I am not concerned, however, in splitting hairs as to the efficiency of generating gas or electricity. I recently showed in a paper before this Institution that gas could be generated at a higher efficiency than that which Sir Dugald claims for town gas. I also showed that it is economical and convenient in some cases to use gas furnaces, but for the transmission and utilization of power over a large works or a scattered area the high efficiency of the gas engine at full load was as nothing compared with the all-round efficiency and convenience attached to the use of electric motors. The benefits are just as well known to the gas industry as to other people. At any large and up-to-date gas-works the management will be found proud of its beauty spot, a gas-driven electric power station. Sir Dugald gave us a very fair and liberal account of the way that he used gas. Last week he was in the Chair in this room at a Meeting of the Gas Institute when unfortunately they did not reach a paper written by Mr. Joseph Fisher, of Tottenham, on " Electricity Supply by Gas Companies." I have made an extract or two from that paper which I think are worth including in the proceedings of this Institution. Mr. Fisher says that he is an " ardent gas man " and then goes on to say: " But in spite of this, five years of electricity supply as a part of his work have shown him that many people will have electricity for lighting if they can get it, even if it costs more; and he has also been astonished at the eager demand experienced for small motors for trade purposes. These motors are installed in places where gas-engines would be quite unsuitable. They are used by people who could not be trusted to attend to a gas-engine; and the small amount of attention and upkeep they require is agreeably surprising. . . . The shopkeepers who had introduced electricity for window lighting extended it to the interior of their premises. They installed half-watt lamps freely, and paradoxical as it may sound, this brought about an increased demand for current. Shopkeepers who had not adopted electricity were practically forced to do so by the brilliance of their neighbours' lighting. . . . Owing to the superior efficiency of electric lamps the writer maintains that there is, from the coal conservation point of view, a decided advantage in using gas to generate electricity instead of burning it directly to heat an incandescent mantle. . . . For power the comparison must naturally be wholly in favour of gas used direct rather than for electricity generated by town's gas. Obviously one cannot generate electricity by gas and reconvert it into power without some loss; but practically there is a great advantage is so doing. It enables a great number of people to use small power units in factories, shops, and even in their homes—in

places where a gas-engine would be quite out of the question, and where it would be impossible to maintain the efficiency of such a number of small engines. . . . Although on paper the advantage is in favour of gas, the writer is confident that in practice the electric system is to be preferred in all cases where there is not a continuous heavy load all the time. . . . Last but not least, the public generally should get the best service. People without technical knowledge would not be rushed into using electrical appliances in cases where gas is in every way better and more economical, and so also there would be no reason to dissuade customers from using electricity where it is obviously the most suitable agent to employ." Thus writes Mr. Fisher, and I have not quoted all that I might have done. I would plead for more sanity and clear thinking in each industry. Some people speak of electricity as if it were a prime mover and, on the other hand, some gas people only recognize electricity as an enemy. The competition of electricity has been the making of the gas industry. Each can, and will, help the other. I firmly believe there is plenty of room for both. But what I am really anxious about is that each will set its face against the pauperizing of its customers at the expense either of the owners of the respective undertakings or of the State.

Colonel R. E. B. Crompton : Having been actively engaged during the last 35 years in the scientific and industrial development of electric supply I have always found it advantageous to be on good terms with the gas authorities, as there are points common to both of us where conference and mutual assistance is desirable. When Sir Dugald Clerk read his paper at the Society of Arts I demurred to some of his comparisons as misleading ; I pointed out that even in the case of electric heating for domestic use it can be shown that the same convenience of application which make the claims for electric-motive power so pre-eminent are sometimes applicable to heating, e.g. when a sick person requires artificial heat in the bedroom, the cost of giving this heat by a radiator placed near the bedside is much less than the cost of heating that bedroom by gas. I have since gone into this matter carefully and have discussed it with my friend Dr. Carpenter, a leading gas authority, who is Chairman of the South Metropolitan Gas Company. I told him that I had used gas for cooking for 35 years, that I had long ago found it too costly for the heating of bedrooms, and that for cooking for my moderate-sized family my bills have averaged from £30 to £40 per year for many years past, and that I thought by careful study this wasteful expenditure might be reduced. Dr. Carpenter sent one of his experts to examine my cooking stoves and I find that the best present practice, on the scale of cooking for a family of 6 people, the average consumption of gas is 180 ft. per day or 30 ft. per person. As London gas is taken as 500 therms per cubic foot this means that 15,000 therms are required to cook, that is to raise about 2 lb. of solids and 5 lb. of liquids or 7 lb. in all through a range of temperature necessary for cooking purposes, if we take this range to be about 150 degrees F. it follows that the total number of therms theoretically required for raising the material to the maximum temperature is 1,050, that is to say, the balance of nearly 14,000 therms is wasted in radiation and other losses or added to those caused by the carelessness of the cook. Knowing how much I owed to Druit Halpin for his study of thermal storage for our generating stations, I made up a 20-gallon water-heating apparatus so protected against radiation losses and with such burners that the water therein never actually boiled, and I was at once struck by the extraordinary economy thus obtained. I reduced the size of the Bunsen burner to such a point that the losses due to radiation and escaping gases were balanced by the consumption of about 1 cub. ft. of gas per hour. I pointed out to Dr. Carpenter that this made me an "immoral" person, as this small quantity was not sufficient to cause the gas meter to read during the all-night hours when the gas supply for ordinary cooking was not used, which was not fair to the gas company. I see no reason why equal economy of electrical modes of heating should not be obtained by similar means. I have called attention to the point as I believe the question to be an important one. The minimizing of losses due to radiation and such-like causes ought to be carefully studied by both gas and electrical engineers. As an old electrical engineer I feel rather pleased with myself for having shown the way to the gas people.

Professor A. Smithells : I think it is all to the good that a discussion between the two industries should be raised to the level reached this evening and should be rescued from that partisanship which is natural but which is very dangerous in some respects when the public and the statesmen of this country have to be led in the right direction on a question of great national importance. I hope that the friendly overtures which have been made in an official way between the two industries may be long continued.

Sir Dugald Clerk *(in reply, communicated)* : I wish to thank the President, the Council and the members of the Institution most heartily for their very kind reception of Professor Smithells, Professor Cobb and myself. They heard the case for gas efficiency in the fairest way and expressed themselves in a friendly manner, not only to us as brother scientific men engaged like them in the search for truth, but they have also sympathized with the desire for progress in the great gas industry. They were all of opinion that the great electrical industry could flourish in co-operation with the gas industry. They recognized that our country had need of the services of both, and looked forward to the great expansion of the gas industry in friendly rivalry with the expanding electrical industry. Undoubtedly both industries will flourish under free competition, provided that both are left free from hampering legal restrictions. To me the attitude of electrical engineers is most gratifying, and leads me to hope for a better understanding between us and more co-operation than has been the case in the past. The gas industry fully recognizes the imperative necessity for electricity as well as gas.

I thank also all those electrical engineers who took part in the discussion and gave us the benefit of their criticism. With regard to this criticism, I had hoped that the question of the actual efficiency figures given in my lecture and in the Clerk-Smithells-Cobb Report

would have been fully examined and discussed. No criticism, however, has been made of those efficiency values, and only a very few references were made to them in the discussion. Mr Wordingham, for example, stated that when a gas engine was running light it was running uneconomically and wasting a large amount of heat. Mr. Merz also questioned the figures given as to efficiency of gas engines running at various loads varying from 20 to 25 per cent, and he stated that these efficiencies were not obtained or kept in practice except in very exceptional circumstances. None of the other speakers questioned the efficiency values given by gas engines.

With regard to Mr. Wordingham's statement, I would point out that even as early as 1905 most ordinary horizontal gas engines in towns were running with coal gas on a 27 per cent brake efficiency of gas at the engine at full load; and at one-third load the brake efficiency was still 20 per cent.

Mr. Merz is quite mistaken in assuming that 20 and 25 per cent are exceptional efficiencies in the ordinary coal-gas engines of to-day; 30 per cent brake efficiency at full load is not at all uncommon. Almost any good modern horizontal gas engine will give 30 per cent brake efficiency at full load and will run with but little reduction down to $\frac{1}{3}$ load.

With regard to heating by electricity, no criticism is made of our figures. Mr. Wordingham, it is true, points out that the ease of turning a switch to produce electric heating or motive power is so great that economies can be made when heat is required for short periods, or motors have to run for similar short periods doing discontinuous work. Gas engineers quite understand the advantage of electricity used in this way, but the main point of my Lecture and the Joint Report has been to show the actual efficiencies in extended and continuous use. I find myself quite in agreement with my colleagues, the electrical engineers, in considering that thermal efficiency is by no means the sole determining factor leading to the use of gas or electricity. Both have conveniences which far exceed those of solid fuel, and, no doubt, both would be used instead of solid fuel in many circumstances.

With regard to Mr. Wordingham's remark as to large gas engines being at present under a cloud, I should like to call his attention to the inverted vertical gas engines which have been rapidly introduced into use during the past eight years, and one firm alone has supplied over 100,000 b.h.p. of these engines in units from 500 to 3,000 h.p. These engines are largely used for generating electricity at collieries and in other places. I quite recognize that for the great central stations now in use it is necessary to go to units very much larger than 3,000 h.p., and consequently the steam turbine finds great use.

I agree with Mr. Merz as to the importance of reducing the cost of labour. All manufacturers ask, How can we produce our products most cheaply? and no doubt cheap motive power is very necessary. The very large and extending use of the smaller gas engines running with town's gas shows how much manufacturers do appreciate such cheap motive power. For work of this kind the gas engine industry shows an ever-increasing expansion which has not been checked in any way by the use of the electric motor. It is true that many of the smaller gas motors up to perhaps 5 h.p. are but little used because of the greater convenience of small electric motors, but the only effect the electric motor has had on the gas-engine industry so far is to push up the average power of individual gas engines. At a certain power it becomes much more economical to use a gas engine for a small works than an electric motor, and accordingly gas engines are so used in very large numbers. I have already pointed out many times that much more than a million horse-power of gas engines are at present in use in Great Britain, many of them operated by coal gas.

I do not quite agree with Mr. Merz and Mr. Sparks as to the limitation of the Coal Conservation Report to motive power. It is true that the 55 or 56 million tons was to be saved out of the 80 millions by electric motive power alone. This estimate, however, I have criticized in the "Forrest" Lecture, and I need not deal further with it here. I would point out, however, that it was necessary for the gas industry to deal not only with motive power and light, but also with electrical heating. Mr. Merz will no doubt remember that this campaign for the general use of electricity for light, power and heat really began with Dr. S. Z. de Ferranti's Presidential Address to the Institution in 1910. Dr. Ferranti made the following statement:

> "It appears that . . . the coal should be converted . . . into a form in which it is most generally applicable to all purposes without exception, and in which it is most easily applied to all our wants, and is at the same time in a form in which it is most difficult to waste or use improperly.
>
> "We are therefore forced to the conclusion that the only complete and final solution of the question is to be obtained by the conversion of the whole of the coal which we use for heat and power into electricity, and the recovery of its by-products at a comparatively small number of great electricity-producing stations. All our wants in the way of light, power, heat and chemical action would then be met by a supply of electricity distributed all over the country."

With this statement Mr. Merz prefaced a paper read by him to the British Association Newcastle Meeting, 1916. His ambition was thus to supply all our wants in the way of light, power, heat and chemical action. I have read the whole of Dr. Ferranti's Address and there is no doubt that this was his intention. Mr. Merz—unconsciously, no doubt—imported that feeling to some extent into the Sub-Committee's Report, and this is evident from the statement of Lord Haldane in the prefatory note to the Interim Report of the Power Generation and Transmission Sub-Committee. Lord Haldane states:

> "The question of the conservation of coal, so far as it falls within the reference . . . is the question of economy in the use of coal through supplying electricity for power and other forms of energy."

There is no limiting here to power alone, and when I read Lord Haldane's Address in the House of Lords dealing with the Electricity Bill I find that he clearly considers gas-works processes to be of a most uneconomical nature and he does not hesitate to say so. These statements Lord Moulton attacked in the House of Lords. Apart altogether from the direct statement in the Committee's Report, the whole effect of the propaganda to obtain large central stations was such as to imply that present processes were wasteful for supplying heat, light and power, and that great economies would be obtained by generating electricity and distributing to supply all these needs. To give one example, in an article by Mr. Sydney Brooks in the *Nineteenth Century and After* of March, 1919, we find this statement:

> "We are all sinners in this wastage of coal—householders, collieries, manufacturers, gas-works—they perhaps are the greatest criminals of all—railways, every person, every firm, every industry that uses it at all."

Such statements were made wholesale, not only in the monthlies, but in many daily papers. Even Mr. Patchell in his remarks seems to have observed this feeling. He says: "Electricity was to be the cure-all. Rivers of electricity were to wash away the effects of the war, if not the whole of the national debt." I can assure Mr. Merz, Mr. Sparks and Mr. Patchell that under these circumstances it was very necessary for the gas industry to bestir itself and show the high economies which were obtained in gas-making processes for the supply of heat, power and light. Mr. Patchell thought that I was barking up the wrong tree because the Coal Conservation Sub-Committee's Report excluded the 20 million tons carbonized annually in gas-works. Surely Mr. Patchell is wrong here. The Report—by general inference, Lord Haldane's statements, footnotes, and so on—clearly included the displacement of the present coal used in gas-works for generating gas.

With regard to Mr. Merz's statement that the figures obtained at some of the largest gas-driven stations in the world were inferior to those obtained at steam-turbine stations, I can only say that there are no really large gas-driven stations at work in Britain, although in one Government factory during the war there were 11,000 h.p. of vertical gas engines under one roof generating current for an electrochemical process. I have not been able to get from Government sources the efficiency figures of this generation, but I would refer Mr. Merz to a recent paper by Mr. Patchell, read within the last month or two before the Institution (*Journal I.E.E.*, 1920, vol. 58, p. 417). He will there find, as the result of a very careful test by Mr. Patchell himself, that the combined thermal efficiency of electrical generation was 19·9 per cent with a relatively small gas-producing plant and gas engines of about 500 h.p. Such figures are very easily obtained in quite small stations. Gas-engine designers, however, are quite conscious of the necessity of increasing the power of the gas engine, and some are even attempting to use gas and oil on a large scale in gas turbines. It may be that in the comparatively near future we may find the gas turbine with a 30 per cent efficiency. That, however, lies in the future. Mr. Patchell does not seem to have noticed that in both Report and Lecture we have dealt with 18½ as well as 8½ per cent thermal efficiency of electricity generation.

I am very much in agreement with Mr. Highfield as to the necessity for co-operation between the two industries, and I quite understand his argument that even cost is not the sole determining factor. In connection with the argument, however, it is interesting to notice Mr. Highfield's comparison, for the boiling of water, between electricity and gas. He states that 2·36 lb. of water could be evaporated from and at the boiling point for a penny with electricity and also gas could evaporate for a penny 12·9 lb., whereas coal could evaporate 60 to 70 lb. It is interesting to see that the ratio of cost between electricity and gas is, roughly, five times—that is, the electricity cost for evaporating water is five times that of gas. I quite appreciate that under some circumstances coal might have a similar advantage over gas at 4s. per thousand, but the gas industry is busily at work in remedying this. The gas industry, as I have recently pointed out, will get much higher efficiencies than are at present available.

In his remarks under the heading "Power," Mr. Sparks assumes that I have confined my comparison between gas and electric power to the case where the thermal efficiency of electrical generation was 8·5 per cent. This is the average value for the United Kingdom as given by Mr. Wilson on behalf of the Coal Controller, but if Mr. Sparks will kindly re-read my Royal Society of Arts Address or the Clerk-Smithells-Cobb Report, he will find that I have also discussed the highest results obtained by gas and electricity where the electricity is generated at an efficiency of 18·5 per cent, and I have shown that for motive power gas is still superior at its highest existing efficiencies. Mr. Sparks is quite in error when he concludes that electricity has a substantial advantage over gas in coal conservation when the best performance of each is considered.

Under the heading "Lighting" Mr. Sparks uses erroneous values for the heat consumption by gas per candle-power produced. He takes one case (page 17 of my paper) where the thermal efficiency of gas production is 65·2 per cent, and he takes from my paper the values of *heat consumption at the gas-works* to produce 1 candle-power in the case of upright type mantle, 82 therms, and inverted type mantle, 47 therms. These values he assumes erroneously to be the thermal consumption in use at the burner, whereas the actual heat consumption at the burner per candle-hour is in the one case $82 \times 0{\cdot}45 = 37$ B.Th.U. per 1 candle-hour and in the other $47 \times 0{\cdot}45 = 21$ B.Th.U. per candle-hour. The efficiency of gas production and distribution in the case given by me is 0·45 or 45 per cent, so that Mr. Sparks should have used the smaller numbers thus:—

$$\frac{18{,}900{,}000}{37} = 512{,}000 \text{ candle-power-hours per ton available to consumer}$$

and $\frac{18{,}900{,}000}{21} = 895{,}000$ " "

The mean value is thus 703 for gas instead of 316, and gas and electricity figures corrected are:—

Gas	703
Electricity	670

Instead of a ratio of 1·2 in favour of electricity as under the conditions given by me as average results for the United Kingdom, Mr. Sparks's calculation when corrected shows $\frac{703}{670} = 1{\cdot}05$, a ratio slightly in favour of gas. The ratio in favour of electricity is here not of a higher order, but on the contrary it is reversed. I am sure that Mr. Sparks will agree with this when he re-examines his use of my figures.

Under "Heating" Mr. Sparks asks for the basis of the efficiency of use values used by me: gas = 42 per cent and electricity 59 per cent. To arrive at the comparison I have taken four typical cases of gas and electricity for heating and from published experiments, attached to each average thermal efficiency. The values are: –

Gas	
Gas fires	65 per cent
Boiling and heating water	60 ,,
Gas cooking by oven	11 ,,
Steel heating	32 ,,
	168 ,,

Electricity	
Electric heating of rooms	100 per cent
Electric heating and boiling water ..	60 ,,
Electric cooking oven (Barker) ..	21 ,,
Industrial metal heating (Hadfield)	54 ,,
	235 ,,

I have assumed in both cases that the use is equal in each of the four items given.

$$\text{Thermal efficiency of use: Gas} = \frac{168}{4} = 42\ \%$$

$$\text{Thermal efficiency of use: Electricity} = \frac{235}{4} = 59\ \%$$

I have already pointed out that it is desirable to have a census of use for the whole country, but meantime I regard the two values 42 and 59 per cent as approximately correct.

Under the heading "Coal consumption for equal performance" Mr. Sparks proposes to exclude heating from the comparison. This appears to me to be unfair in view of the strong claims put forward by electrical engineers for a general service of heat, power and light. But even if heat be excluded no saving at all can be shown for electricity in the supply of power and light as compared with gas.

Under the heading "Future co-operation" Mr. Sparks fails to grasp the line of advance now followed by the gas industry which will soon reduce the proportion of coke produced to any desired value as determined by market values.

I quite understand Mr. Patchell's views, which in many particulars closely resemble my own. My paper and the Report both deal with electrical generating efficiencies up to 18·5 per cent, so that I need not further discuss the comparison at high efficiencies.

I am glad to hear Colonel Crompton give such an encouraging account of his experience with gas as a heating agent. The gas industry will be delighted to accept his co-operation.

PERMANENT MAGNETS IN THEORY AND PRACTICE.

By S. Evershed, Member.

(*Paper received* 15 *March, and read before* The Institution, 13 *May*, 1920.)

Preface.

For some time past the author has had in preparation a paper dealing with many practical matters which arise in making permanent magnets. It would be hard to find a manufacture more entangled in occult molecular phenomena, and it soon became apparent that to treat the subject without some kind of theoretical basis would be much like building on quicksand. Textbook theory is too remote from modern ideas about magnetism to afford a satisfactory basis for practice, and the present paper has therefore been undertaken with the object of providing a theoretical foundation more in keeping with present-day knowledge.

The first part of the paper contains an account of the theory of permanent magnetism which combines Ampère's hypothesis of molecular currents with Ewing's theory of the interactions between the magnetic molecules. The ideas to which the conception of molecular currents, and the assumption of one universal magnetic medium, naturally give rise, are developed from a modern point of view, and the elementary principle on which the predetermination of permanent magnets depends is derived from the simple proportionality between magnetomotive force and magnetic induction.

In the second part of the paper two fundamental equations are first established for the case of magnets of uniform flux density; the first of these equations being a statement of the law of maximum external energy which underlies economic design. Ordinary magnets of uniform sectional area are then dealt with, and a full description is given of the author's alternative methods of forecasting the energy output of permanent magnets.

The second part of the paper, therefore, forms a link between theory and practice, and it is proposed to follow it with a paper devoted to the practical branch of the subject.

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PART I.

THE INTERNAL MECHANISM OF A PERMANENT MAGNET.

(1) Introductory.

Anyone who has to do with permanent magnets naturally asks himself, sooner or later, how a magnet works; what is the internal magnetic mechanism which enables it to maintain a magnetic field in surrounding space. And if a permanent magnet is to be designed for

any particular purpose, further questions arise which demand numerical answers. What *strength* of field will a magnet of given dimensions maintain in any given space, or conversely what *dimensions* must be given to a permanent magnet which is required to maintain a field or flux of specified value in a given space? In other words, how is the performance of a permanent magnet to be predetermined; how are we to set about making a numerical forecast of what it will do?

General explanations of the action of permanent magnets are to be found in the textbooks, and there is, besides, a good deal of information to be found by searching for it among scattered papers dealing with different aspects of permanent magnetism.* But although the literature of the subject is voluminous, it is mainly a disconnected record of uncorrelated facts, and it may be searched in vain for any comprehensive account of the theory of permanent magnetism as it stands to-day. Nor does it appear that anything has been published which solves the problem of the designer by putting him in the way of finding numerical answers to the questions with which he is confronted. In the absence of any established method, the author has, for many years past, endeavoured to answer the essential questions of design and predetermination, by building up a working theory of the permanent magnet founded on the experimental and theoretical knowledge we possess in connection with permanent magnetism, and it is proposed in the present paper first to give a general account of the theoretical foundation and then to explain the method of predetermining the performance of magnets which the author has developed for his own use.

So far as design and predetermination are concerned, the basis is to be found in the demagnetization curve; and in practice it is not necessary to look beyond the cyclic curve of the steel in designing a magnet or forecasting what it will do. But the object of this paper is not merely to give a solution of the practical problem. Its wider aim is to bring practice and fundamental theory into line, and something more than a bald description of the arithmetical process of predetermination is needed. It will not be enough to show that a magnet of such and such dimensions will maintain so much magnetic energy in external space; if the paper is in any degree to achieve its purpose an attempt must be made to trace the energy to its source inside the magnet, and to obtain an insight into the internal actions that govern the amount of external and therefore available energy which a permanent magnet can maintain. The paper must necessarily cover a good deal of ground; moreover, the subject is beset with difficulties on the theoretical side, and being for the most part beyond the range of mathematical treatment, lengthy verbal explanations must take the place of the convenient short cuts provided by mathematical analysis. On the practical side, the author's method of predetermination will be described in sufficient detail for anyone to make use of it, and a few practical examples will be given, illustrating the application of the method to types of magnet representing those in common use.

* An extensive bibliography of the subject was appended by the late Dr. S. P. Thompson to the lecture on permanent magnets (*Journal I.E.E.*, 1913, vol. 50, p. 80) which he gave to the Glasgow Local Centre a few years before his death. The lecture itself is an admirable summary of the state of knowledge at the time it was delivered.

(2) The Theory of Magnetic Attractive Matter.

There are, of course, two ways of regarding a magnet. The earlier workers, experimenting with bar magnets, discovered that the attractive and repulsive forces between the ends of the bars obeyed the law of inverse squares with considerable accuracy. This, and the influence of Newton, led to the conception of magnetic poles from which the force was assumed to radiate equally in all directions. It was also discovered that every particle of steel in a magnet was itself a little elementary magnet. Upon these facts a mathematical theory was founded by assuming that the observed attractive forces were due to imaginary magnetic attractive matter distributed in a layer of varying thickness over the surface of the magnet. Attraction and repulsion were accounted for by supposing the magnetic matter to be of two kinds, positive and negative—north and south, or, as Lord Kelvin used to speak of it, red and blue magnetism. The theory took no account of the significant magnetic properties of the steel of which the magnet was made, and, as regards the forces at work in surrounding space, action at a distance was tacitly assumed.

Such a theory could not be expected to carry us very far, yet in the unique case of the magnetized ellipsoid if gave a complete mathematical solution of a problem which has, so far, not been solved in a mathematical sense for any other shape of magnet. As we shall see in a later section, the theory of the ellipsoid founded on hypothetical magnetic matter, when used in conjunction with present-day knowledge of the magnetic properties of steel as represented by the cyclic curve of magnetization, enables the performance of a permanent magnet of that particular shape to be predetermined with accuracy. But beyond that unique case the older theory does not provide a basis to work upon, and to forecast the performance of magnets of the ordinary forms used in practice we must turn elsewhere for guidance.

(3) Hopkinson's Method of Predetermining the Performance of Electromagnets.

The work of Faraday, and more especially his wonderful insight and power of grasping the essence of phenomena, entirely changed the older perspective. To his mind, action at a distance was unthinkable, and when he looked at a magnet he saw, in imagination, lines of force extending from the magnet throughout the surrounding magnetic field and serving as the means of transmission of the observed mechanical forces between one magnet and another. And since the lines of force or induction passing through the magnet were continuous, leaving it at one pole and, after traversing the magnetic field, returning to it at the other pole, the conception of a magnetic circuit naturally followed; the magnetic circuit forming a continuous path, as it were, traversed by the magnetic flux and constituting what is called a tube of force, or tube of flux. On this basis Hopkinson solved the problem of forecasting the performance of a dynamo. Rejecting empirical formulæ, he showed that the necessary total excitation to produce the required magnetic flux could be ascertained by direct reference to magnetization curves obtained from samples of the iron or steel

employed in the field magnet and armature ; the magnetic potential difference between the ends of each component part of the magnetic circuit being deduced from the corresponding curve. Hopkinson's method is, therefore, a process of summation or integration of potential differences, proceeding step by step round the magnetic circuit and arriving finally at the total magnetomotive force which must be supplied by the field coils.

(4) Extension of Hopkinson's Method to Permanent Magnets.

Following Hopkinson, the author predetermines the performance of permanent magnets by a somewhat similar process of step-by-step integration round the complicated bundle of magnetic circuits formed by a permanent magnet and its external field, referring at each step to the cyclic curve of the steel from which the magnet is to be made. The main difficulty in dealing with a permanent magnet on this basis lies in the fact that in place of a single extraneous magnetomotive force located in the field coil of the electromagnet, we have an inherent magnetomotive force located inside the magnet steel and, in general, of varying magnitude along the length of the magnet. The difficulty arising from this additional complexity is surmounted by performing simultaneous step-by-step integrations of both potential difference and flux density.

The method, which will be fully explained in the second part of this paper, is readily applicable to any permanent magnet in which the magnet and its external field constitute a fairly well-defined magnetic circuit ; a condition which covers all the ordinary forms which occur in practice, with one exception. The one outstanding exception, which is excluded from the present paper, is the ordinary bar magnet of uniform cross-sectional area. Although the total flux in a bar magnet of this kind can be predetermined with some approach to accuracy,* the more difficult problem of forecasting the law of variation in flux density along such a bar has hitherto proved intractable, and in the absence of a solution it is not possible to do more than make a rough forecast of the field created by an ordinary bar magnet at any given point in surrounding space. The unique case of the bar magnet of ellipsoidal form has already been mentioned. Its singularity consists in the fact that in an ellipsoid the flux density is uniform throughout, and hence the difficulty which arises from the varying density in the ordinary bar magnet does not exist, and the ellipsoid comes within the province of the mathematician.

(5) The Magnetic Energy maintained by Permanent Magnets.

A permanent magnet is a source of magnetic energy ; some part of the energy appearing in that part of the magnetic circuit which lies outside the magnet, where it is maintained by the surplus magnetomotive force of the magnet steel. The product of the total surplus magnetomotive force into the magnetic flux constitutes the external energy which is available for use in any place where it is desired to have a magnetic field or magnetic flux. It will be shown that the external or available energy may be readily deduced from the cyclic curve of the steel of which any given magnet is made, and that the maximum external energy which can be maintained by a unit volume of any kind of steel is the criterion by which the magnetic value of the steel, as a material for permanent magnets, should be judged.

* A rough method for the purpose is given in the Appendix, as an illustration of the application of the spherical pole formula.

(6) The Ampère-Ewing Theory.

We must first look to the origin of the external energy maintained by a magnet. The only known source of what is called magnetic induction, or flux, or field, is an electric current, and Ampère long ago guessed that if we could look inside a permanent magnet we should find electric currents flowing in molecular circuits. From the modern standpoint the molecular current is no longer in doubt, and permanent magnetism must be explained in terms of Ampère's hypothesis and Ewing's theory of the interactions between neighbouring magnetic molecules or elements. The ability of a mass of Ampère elements to act as a permanent magnet depends on their margin of stability as regards the equilibrium of mechanical forces within the system, forces which arise from the action of the molecular currents ; and before coming to the principle which forms the basis for the predetermination of permanent magnets, it will be necessary to consider at some length the conditions which govern molecular equilibrium in any magnetic substance like iron or steel. The forces to be taken into account are far too complex for mathematical treatment, and the subject can only be dealt with in a general way.

Ewing's theory is well known and needs no description here, beyond a brief statement of the underlying principle. It affords a rational explanation of the highly complicated phenomena of induction in magnetizable substances ; many confusing effects of temperature, mechanical stress, hysteresis and so on, falling easily into their right places and forming parts in a reasonably consistent whole. In applying the theory to the case of the permanent magnet it is only necessary to follow the stages through which the steel is carried in the course of initial magnetization as a magnet ; we are not concerned with hysteresis, nor is any reference to temperature and other effects called for in the present paper.

The fact that any small particle of steel in a permanent magnet is itself a little magnet long ago suggested the idea that the ultimate elements of molecular or atomic dimensions were also, in effect, permanent magnets. Weber assumed that molecules of iron were in reality permanent magnets, and he did not find it necessary to inquire why they were magnets. On the other hand, Ampère supposed each molecule of iron to be an electric circuit of no resistance in which a permanent electric current flowed, so that the molecule behaved like a little magnet. In the virgin state of the steel the molecular elements, whether of the Weber or of the Ampère type, were assumed to have the direction of their magnetic axes disposed at random, so that in the aggregate they produced no observable magnetic effect, the process of magnetization consisting in orienting the molecules more or less in one direction by means of an externally applied magnetizing or orienting force. Various hypotheses of an artificial kind were

devised to account for the peculiar relation between the applied force and the resulting magnetization, without, however, arriving at a satisfactory explanation of the facts, so far as they were known.

At a later time when the cyclic character of the magnetization curve had been recognized and investigated by many workers, Ewing swept away the whole of the rather fantastic hypotheses for the control of the magnetic molecules, by showing that if we supposed each molecule to be free to turn about a pivotal axis at right angles to its magnetic axis, the ordinary magnetic attractions and repulsions, which would naturally take place between neighbouring magnetic molecules, were alone sufficient to account for every characteristic feature of the highly complicated cyclic curve. The interplay of the turning-moments which adjacent molecules exert on each other in this way is beyond the scope of mathematical demonstration, but the Ewing model, which consisted of a group of 20 or 30 freely pivoted little permanent magnets—representing a group of Weber elements—faithfully reproduced all the features of the cyclic curve of magnetization and demonstrated the substantial truth of Ewing's theory.

It need hardly be pointed out that models are not necessarily proofs. A model is often based solely on analogy; there is a coincidence of effect without any real identity of action. But the Ewing model rests on firmer ground than mere analogy. Like the steel which it is intended to represent, it is built up of little magnetic elements. It is controlled solely by the inherent magnetic attractions and repulsions of the little magnets, and since it reproduces the exceedingly complicated phenomena represented by the cyclic curve the chances in favour of identity of action, and against accidental coincidence, are enormous. We are therefore justified in believing that the invisible actions going on inside a magnetizable substance like iron or steel are, broadly speaking, identical with the actions which visibly take place in the model.

(7) Adaptation of Ewing's Theory to Ampère's Molecular Circuits.

Ewing's theory was published nearly thirty years ago and much has happened in the meantime to clear up matters which were then in doubt. The discovery of the electron by Sir J. J. Thomson, and the evolution of a theory of the atom as a system of electrons moving with very high velocity in orbits round a centre or nucleus, have definitely turned the scales in favour of Ampère's hypothesis. The existence of the molecular current will therefore be assumed; but for mental convenience the magnetic molecule with its complicated system of electronic currents will be represented by an imaginary circuit or *current ring*, carrying a permanent and constant current, and behaving like the actual molecule so far as magnetic actions on neighbouring molecules and surrounding space are concerned.

In treating of permanent magnets we shall therefore regard a piece of steel as composed of a crowd of current rings, and it will be assumed that each current ring is free to rotate, or rather to deflect, about any diameter in the plane of the ring; in other words that it has a pivotal axis at right angles to its magnetic axis. In the initial or virgin state of the steel the current rings are supposed to be arranged, not exactly at random, as regards their individual orientations, but in groups which form more or less self-contained systems held together by magnetic bonds of mutual induction, so that an assemblage of similar groups will have no resultant magnetomotive force to create induction in any one direction. So far we are following Ewing, and the process of orientation of such a mass of current rings does not differ in principle from that which has been so fully described by Ewing himself in connection with a crowd of Weber elements.*

But our point of view naturally undergoes a change when we substitute Ampère elements or current rings for the little Weber elements, and it becomes possible to recognize certain broad principles underlying the magnetic equilibrium of a mass of current rings under the control of their own inherent forces. Although it is not practicable to follow the motions of any individual current ring, or to determine the law of the complicated forces exerted on it by its neighbours, it is possible by dealing with current rings in the mass to determine both the general character of the forces which control their average angle of orientation, and the nature of the conditions which govern the stability of the whole mass as an oriented system of magnetomotive forces.

In the first place, it may be assumed that the magnetic medium in which the current rings are immersed is the universal magnetic medium of space. The assumption that there is only one magnetic medium to be reckoned with greatly simplifies our notions about magnetism because the relation between the two fundamental quantities, namely the magnetomotive force of an electric current and the resulting state of things in the medium which goes by the names induction, magnetic flux, or magnetic field, will everywhere and under all circumstances be the same. And although we do not yet understand the nature of the mechanism by which the current creates the induction, we do know by experiment that the induction is strictly proportional to the magnetomotive force of the current.

(8) Terms, Definitions, and Symbols.

Permanent magnetism has a long history and has given rise to a medley of terms which have become embedded in the language of science, although some of them have long since become divorced from their primitive sense or even lost their physical significance.† In treating the subject from a somewhat novel point of view, it will therefore be well at the outset to define the sense in which certain terms will be used. Since it is intended to apply the principle of the magnetic circuit to the permanent magnet, the fundamental quantities will be the magnetomotive force acting in the circuit, the reluctance (or the magnetic conductance) of the circuit, and the magnetic flux which is maintained in the circuit by the magnetomotive force. It need hardly be said that although these phrases all suggest a something moving along, they are used conventionally and are not intended to commit us to any theory as to what is actually going on in the magnetic medium. With our present knowledge, all we are justified in saying is that to maintain the state of things

* J. A. Ewing: "Magnetic Induction in Iron and other Metals," 1893, chap. xi.

† The continued use of scientific terms which have changed their meaning seems quite unavoidable; and so long as we know what is meant by them their use does no particular harm as a rule. We still speak of the sun rising, though astronomers now explain the phenomena of sunrise in another way.

called magnetic induction, a magnetomotive force is required; what that state of things may really be, we do not know.

Quantity Defined.

*Symbol.**

F Magnetomotive force inherent in a magnetized body; reckoned per cm. length. For brevity it may be called motive force.

f Motive force expended inside the magnetized body; reckoned per cm. length.

ϕ Surplus motive force of a magnetized body; reckoned per cm. length. A term which refers to that part of the motive force F per cm., which, not being expended inside the magnetized body, becomes a surplus available for use elsewhere. $F = f + \phi$.

H Extraneously applied motive force acting inside a magnetized body or mass of current rings; reckoned per cm. length.

R, r Magnetic reluctance.

k Magnetic conductance.

B Magnetic flux.

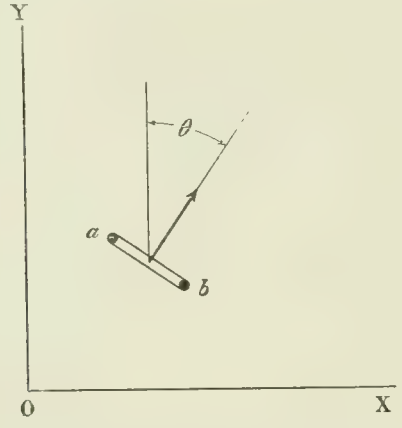


FIG. 1.—Orientation angle θ of a current ring $a\,b$.

The arrow indicates the direction of the magnetomotive force of the current ring.

B Resultant flux density created by the combined action of F and H.

β The magnetic induction. The word induction will be used in the original sense, namely that magnetic condition in space which is created by the inherent magnetomotive forces of a magnetized body or oriented mass of current rings. When an extraneous motive force H is present $B = \beta \pm H$, numerically.

V The total surplus motive force available for use outside a magnet; in other words V is what may be called the terminal potential difference maintained by the aggregate motive force of the magnet.

i The strength of the electric current in a current ring, or magnetic molecule.

s The area of the current ring or molecular circuit.

N The number of current rings or magnetic molecules in a cubic cm.

d The average distance between the centres of contiguous magnetic molecules.

* See Note on page 825.

X Y. Rectangular co-ordinates will be used. The magnetic circuit is supposed to be drawn as a development in a straight line, the magnetic axis being the axis of x.

θ The effective angle to which the current rings in a magnetized body have been oriented. It is the angle of inclination between the effective or resultant direction of the magnetic axes of a mass of current rings, and the axis of y, or Y direction, see Fig. 1. This convention as to the datum from which θ is measured is adopted in order that an increase in θ may result in an increase in the effective motive force F acting in the X direction. θ is an angle such that $n \sin\theta$ is the algebraic sum of the sines of the individual angles of inclination of n current rings.

(9) The Motive Force of a Mass of Oriented Current Rings.

On Ampère's theory the properties of a mass of current rings will apply to all magnetizable substances, but for simplicity of statement the magnetic body will be referred to throughout as iron or steel. Let us suppose that a piece of unmagnetized iron, that is to say a mass of current rings in which the orientation angle is zero, has been subjected to the magnetic field of an extraneous motive force acting in the X direction. Immersed in the extraneously applied field, the current rings are acted on by torques tending to deflect them on their pivotal axes and bring their magnetic axes into line with the applied field. We may call the applied field the magnetizing force, provided we understand its action. What it does is to apply an orienting torque to every current ring; it does not "magnetize" anything. Now let the applied field be removed leaving the mass of current rings in a more or less oriented condition, which is defined by their orientation angle θ. The magnetized or oriented piece of iron will now possess an inherent motive force in the X direction, the oriented mass of rings creating induction in that direction.

The effective motive force of the oriented mass may be found as follows: If a straight line is drawn anywhere through the mass parallel with the X direction, the motive force along the line will evidently be $4\pi n i$, where n denotes the number of current rings threaded by the line per cm. of length. We may imagine the entire volume occupied by the mass of rings to be traversed by similar straight lines, uniformly spaced and all parallel with the X direction; and if there are g lines per sq. cm., the number of lines threading an average current ring will be $g s \sin\theta$, where $s \sin\theta$ is the projected area of the current ring. The average number of current rings in a cubic cm. being N and the length and sectional area of the mass of rings being denoted by L and A respectively, the product of the total number of rings into lines threaded will be $N L A g s \sin\theta$. But the total number of lines traversing the mass will be gA, and hence the number of current rings threaded by an average line will be $N L A g s \sin\theta / (g A)$ which is $N L s \sin\theta$. Hence n, the number of current rings threaded by the average line in a centimetre of its length, will be $s N \sin\theta$ and the motive force along any line parallel with the X direction will be

$$F = 4\pi n i = 4\pi s i N \sin\theta \quad . \quad . \quad . \quad . \quad (1)$$

When θ is a right angle, that is to say when all the current rings are completely oriented in the X direction so that $\sin\theta = 1$, the motive force per cm. attains its maximum value $F_m = 4\pi siN$ so that we may put

$$F = F_m \sin\theta \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

(10) Systematic Distribution of Current Rings.

It is a matter of common observation that when a piece of iron has been magnetized it retains some of the magnetization after the removal of the extraneous magnetizing force. The oriented current rings are therefore in equilibrium when the iron is in the permanently magnetized state, and it requires the application of an extraneous field in the positive direction to increase the orientation, and in the negative direction to decrease it. Equilibrium implies that the algebraic sum of the torques acting on any current ring is zero, and the origin of the mechanical forces acting on the current rings must now be considered.

Assuming the atomic currents to be constant, any two or more current rings will tend to turn on their pivotal axes in directions which will increase their joint energy. Hence a mass of rings, like that shown at I in Fig. 2, cannot be in stable equilibrium, because the magnetic axes of the rings are pointing indifferently in all directions and the only energy in the mass is that arising from the self-induction of individual rings. Evidently the energy of the mass will be increased if any two or more rings turn round until they possess a magnetic axis in common, and so create for themselves a bond of mutual induction. General movements of rotation would therefore go on throughout such a mass until some kind of systematic grouping of motive forces had given rise to a number of bonds of mutual induction, serving to hold the whole mass of rings in stable equilibrium. If we imagine the current rings to be uniformly distributed throughout the mass, the simplest form in which they can arrange themselves in equilibrium, in the absence of any extraneous force, is that shown at II, which may be regarded as a typical example of the primitive condition of a piece of iron before it has

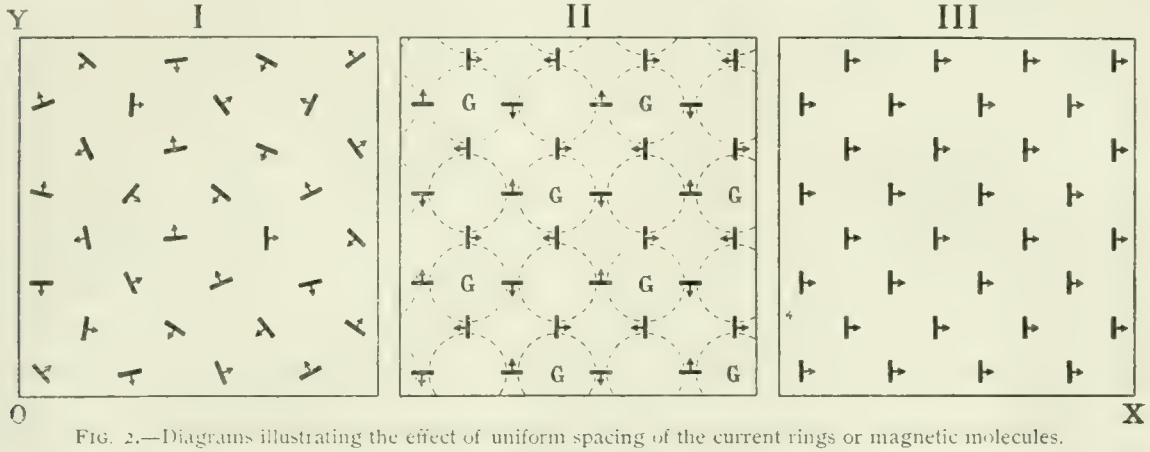


Fig. 2.—Diagrams illustrating the effect of uniform spacing of the current rings or magnetic molecules.

I. Current rings pointing at random. $\theta = 0°$.
II. Current rings in orderly self-contained groupings; $\theta = 0°$.
III. Current rings after the application of an orienting field; $\theta = 90°$.

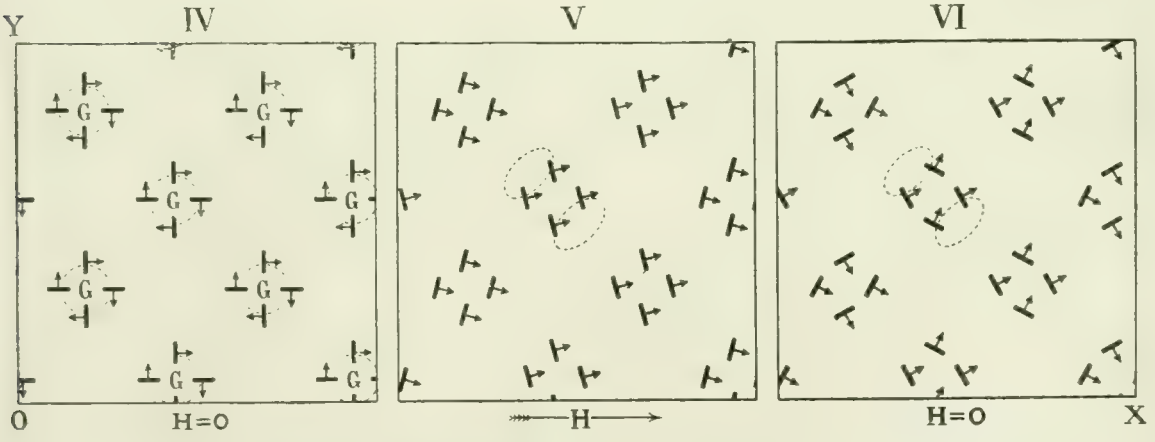


Fig. 3.—Diagrams showing the effect of gathering the current rings together into concentrated groups.

IV. Groups in the self-contained state. $\theta = 0$.
V. Groups under the action of a strong orienting field; θ nearly 90°.
VI. Oriented groups in the remanent state after removal of the orienting field; θ about 45°.

been magnetized; the orientation angle being, in effect, zero. In this state the current rings are held in systematic angular positions by bonds of mutual induction which are indicated in the diagram by the circular dotted lines representing the magnetic axes of the groups.

If an extraneous motive force of gradually increasing strength is applied to a mass of current rings in the primitive or self-contained condition (II, Fig. 2) the torque exerted on the rings by the extraneous field will deflect them against the opposing torques due to their mutual induction. As the deflections increase there will be a gradual diminution in the component motive forces which create the mutual induction, and a corresponding decrease in the opposing torques, until at length when the applied torque exceeds the remaining strength of the mutual induction bonds there will be nothing to prevent the current rings from turning round until they have one and all set themselves with their magnetic axes in alignment with the extraneous field, as shown at III. In this completely oriented state the mass will once more be in equilibrium, and if the extraneous force is removed the current rings will retain their oriented positions by virtue of the general induction through the whole mass, created by the resultant inherent motive force of the oriented system; the magnitude of the motive force being $4\pi si\mathbf{N}$, and the energy a maximum. The mass of rings has therefore passed from one condition of equilibrium to another through a transitional stage of instability; the orienting process having been opposed by the negative torques arising from the mutual induction which held the current rings together in the primitive or self-contained condition. As in the case of the effective angular position of a number of current rings, the torques which arise from the mutual induction of self-contained or closed groups, like those shown at II (Fig. 2), may be represented by an equivalent torque acting on the average current ring, and the negative torque arising in this way is one of the several torques to be taken into account.

With the imaginary uniform distribution shown at II (Fig. 2), complete orientation would take place when once the primitive bonds of mutual induction had been broken by the extraneous force. No magnetic material is known which behaves in this way, the permanently oriented or remanent state in iron or steel, for example, falling very far short of complete orientation. But with uniform distribution of current rings there is no intermediate condition of equilibrium between the self-contained arrangement and the fully oriented state, and we are therefore led to infer that in iron and other magnetic substances there is some lack of uniformity which has the effect of giving the magnetic molecules stability as an oriented system at some angle less than complete orientation. A simple modification in distribution would suffice to give the required stability. The primitive condition shown at II, as a plan in two dimensions, represents a system of cubical groups of eight current rings arranged about the centres GG, and the modification might consist in a gathering together of the eight rings, a shrinkage of the group, which would decrease the size of the cube. In this way the current rings in any individual group having been drawn closer together about the centre G, the group would have become more or less detached from its neighbours; a concentration which makes no change in the average number of rings or magnetic molecules in unit volume, but releases the group to some extent from the influence of neighbouring groups and enables it to act as a more or less independent unit. An example of the modified distribution is shown at IV (Fig. 3); an imaginary arrangement which may be described as a uniform distribution of concentrated cubical groups. Concentration of this kind provides a more or less free space outside each group, which enables an oriented group to form complete local magnetic circuits passing through the current rings and returning through the free space. The current rings in a concentrated group are therefore able to maintain a flux in these local paths, which will serve as a magnetic bond to hold them together as an oriented group. Each group will have its own natural magnetic axis of orientation, an axis which upon the average will be inclined to the direction of the extraneous force, and, on orientation of the whole mass each concentrated group will arrange itself as an oriented local system. Oriented groups of this kind are shown in V and VI (Fig. 3); and since they have been formed during the transitional stage in which the current rings, having been released from the primitive induction bonds shown in IV, are turning round under the influence of the orienting field towards the direction in which that field is applied, the magnetic axes of the groups, after orientation, must necessarily point more or less in the direction of the applied field. That is to say they will all point somewhere within a right angle of the X direction; they cannot point backwards.

(11) Tribal Conditions of Orientation.

Following Ewing, we shall suppose that in a piece of iron or steel, of sufficient size to contain a large number of crystals, there will be tribes of molecules regularly formed in parallel lines of groups, as indicated in the diagrams, the different tribes presenting every possible variety of aspect as regards the inclination of the lines of groups to the direction of the extraneous applied force. Hence after orientation in the X direction the magnetic axes of the concentrated groups, in any considerable mass, will point in every direction which it is possible for them to acquire while they are arranging themselves during the transitional stage. In other words the magnetic axes of the groups will have every variety of direction between 0° and 180°, and since complementary angles in the two quadrants 0° to 90° and 180° to 90° have the same effect as regards motive force created in the X direction, the mean angle of orientation will be 45°. The diagrams of imaginary arrangements show portions of an individual tribe, and for simplicity the inclination of the lines of groups with regard to the X direction has been made 45°, in order to correspond with what we may suppose to be the average aspect of a number of tribes. Hence the oriented groups shown at V and VI (Fig. 3) have their magnetic axes pointing in two complementary directions only, namely 45° and 180°−45°, which in state VI makes the effective angle of orientation in the X direction equal to 45°; this being the remanent condition of orientation of the imaginary arrangement.

The orientation of the individual current rings may be pushed beyond the condition shown in VI by the application of an extraneous field, and in the limit every ring

might be oriented to 90°. But on the removal of the extraneous field the current rings will return to the angular position they naturally occupy as members of locally oriented groups and the remanent condition shown at VI (Fig. 3) will be restored.

In diagrams V and VI (Fig. 3) the oriented groups are directed indifferently at the two complementary angles; but if the principle of maximum energy is applied, it is clear that such an arrangement, although it might be possible for the individual tribe, would have no stability in the presence of other tribes of complementary aspect. For example, if the concentrated groups in two contiguous tribes, like those shown at VII and VIII in Fig. 4, arrange themselves systematically during the transitional stage so that all groups in tribe VII have their magnetic axes at 45°, and all those in tribe VIII at 180°–45°, then in each tribe there will be a component motive force at right angles to the X direction, and the two tribes will act together to create a flux in a local or tribal magnetic circuit, the axis of which is indicated in the diagram by the broken line. Now a systematic tribal arrangement of this kind in no way affects the motive force in the X direction nor does it involve any change in the local energy of the individual groups. Hence the orderly direction of the magnetic axes of the groups in adjacent tribes increases the energy of the whole system, and in the absence of anything to prevent it some such orderly tribal arrangement must be the final condition after orientation. The tribal magnetic circuits may be supposed to present every variety of aspect towards the X direction, but whatever the aspect of an individual tribal circuit (or local whirlpool of flux) may be, those parts in which the flux has the same direction as the useful flux in the X direction will cancel corresponding parts of the local circuit in which the two directions are contrary, and in effect we have only to take into account those parts of the tribal circuits which have a direction at right angles to the X direction. In other words it will only be necessary to consider the local tribal induction as having a transverse or Y direction. The principle of maximum energy strongly suggests the tribal condition as a consequence of orientation, and there is a certain amount of experimental evidence pointing to the same conclusion. The existence of tribes of molecules implies tribal boundaries of some kind, and it may be that in crystalline substances, like iron and steel, each minute crystal constitutes a tribe.

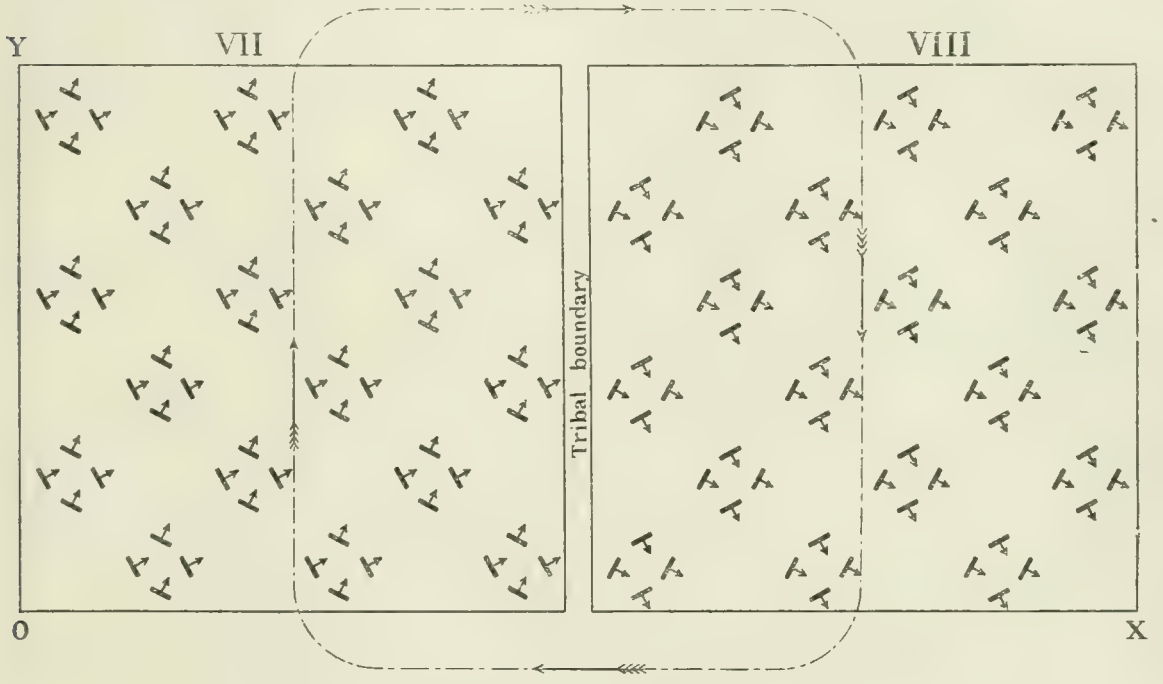


FIG. 4.—Diagram showing effect of systematic tribal orientation of concentrated groups of current rings.

(12) THE EQUILIBRIUM OF A MASS OF CURRENT RINGS.

Assuming that the molecular or crystalline structure of iron lends itself to tribal conditions with transverse induction, the torques acting on the average current ring in an oriented mass will arise in four ways, namely, (1) from the useful induction β in the X direction, this being what may be called the principal torque; (2) from the transverse induction β_y due to the tribal condition, which may be referred to as the tribal torque; (3) from the rate of change of the mutual induction of closed or self-contained groups; and (4) from the rate of change of the mutual induction of oriented groups. In addition to these four torques which are all inherent in the oriented system of current rings, there may of course be a torque arising from an applied field created by an extraneous motive force. Taking the inherent torques in order, that due to the induction in the X direction will be $\beta s i \cos\theta$, and since the motive force in that direction is $4\pi s i \mathbf{N} \sin\theta$

we may put $\beta = k_x s i \mathbf{N} \sin\theta$, where k_x is a constant proportional to the magnetic conductance in the X direction. Torque (1) is therefore $k_x s^2 i^2 \mathbf{N} \sin\theta\cos\theta$. Similarly if β_y is the transverse induction, torque (2) will be $\beta_y s i \sin\theta$, and the component of motive force acting in the Y direction being $4\pi s i \mathbf{N}\cos\theta$ we shall have $\beta_y = k_y s i \cos\theta$, so that torque (2) will be $k_y s^2 i^2 \mathbf{N}\cos\theta \sin\theta$. Torque (1) tends to increase θ, torque (2) to decrease θ; that is to say the principal torque acts in a positive sense and the tribal torque in a negative sense. Since these two torques are the same function of θ they may be conveniently reckoned together as a single resultant torque $\mathrm{P} = (k_x - k_y) s^2 i^2 \mathbf{N} \sin\theta\cos\theta$.

Torques (3) and (4) arise from the action of the flux in the local magnetic circuits of concentrated groups when the current rings are deflected more or less away from the angular positions which they would occupy as members of oriented groups, in the absence of a deflecting torque. These torques are therefore proportional to the product $s^2 i^2$ and to the number of current rings in unit volume; they will also evidently depend on the degree of concentration in the groups. Since the deflections concerned form part of the general orientation of the mass, torques (3) and (4) must each depend on the value of θ; the relation between torque and angle is, however, of an exceedingly complicated nature and cannot be expressed by any known function of θ. We must therefore be content to represent the unknown functions (and incidentally our ignorance) by symbols; letting u stand for the function of θ appropriate to the deflection of current rings in oriented groups, and v for the corresponding function belonging to self-contained or closed groups. Combining these two torques as a single resultant group torque, and denoting its value under any particular conditions by G, we may put $\mathrm{G} = s^2 i^2 \mathbf{N} (g u - j v)$, where g and j are constants depending on the geometry of the system of current rings and the degree of concentration in groups. With a perfectly uniform distribution, entirely free from concentration, g and j will be zero and the group torque vanishes. Of the two functions u and v, the latter will always be negative, the current rings in a closed group naturally tending towards zero orientation. On the other hand, the sign of u depends on the particular stage of orientation. During the earlier stages of orientation when oriented groups are in process of formation u is positive, but in the later stages when the current rings in oriented groups are deflected beyond their natural position as members of groups, u becomes negative. During the process of demagnetization it becomes positive again as soon as the deflections begin to take place towards zero angle, and, being the predominant term during that stage, $g u - j v$ is also positive.

The particular deflectional condition of the current rings in closed and oriented groups will depend not only on the stage or orientation, that is to say, the transitional stage from closed to oriented groups or vice versa, but also on the initial condition of groups as regards the deflections of their members at the time when the process of transition began. In other words, the group torque G will depend on the previous history of the mass of rings; on the initial state and sequence of changes preceding any particular stage of transition or orientation. Hence for any particular value of θ the functions u and v may have a number of different values depending, as it were, on the route by which θ has been arrived at, and G is therefore a many valued function. It should be noticed, however, that if two masses of current rings (two pieces of iron) having the same product $s i \mathbf{N}$ and the same degree of concentration, are brought from identical initial states by the same route to the same final angle θ, then the group torque G will have the same value in both masses; because the current rings will have been subjected to the same sequence of changing torques and, on an average, they will have arranged themselves in the same fashion.

(13) Tentative Equation of the Torques Acting on an Average Current Ring. Dependence of Coercive Force on Concentration.

Assuming the presence of an extraneous motive force $\mathbf{H}$ acting in the X direction and creating a field numerically equal to $\mathbf{H}$, there will be an applied torque $\mathbf{H} s i \cos\theta$ in addition to the inherent torques, and the equation of equilibrium will be $\mathrm{G} = \mathrm{P} \pm \mathbf{H} s i \cos\theta$, or

$$s^2 i^2 \mathbf{N} (g u - j v) - (k_x \quad k_y) s^2 i^2 \mathbf{N} \sin\theta\cos\theta \pm \mathbf{H} s i \cos\theta \quad (3)$$

This equation is very far from being a complete statement of the conditions for equilibrium, nevertheless one or two useful deductions may be drawn from it. In the particular case when $\mathbf{H}$ is applied in the negative direction and so adjusted in magnitude as to reduce the remanence flux in the X direction to zero, so that $\theta = 0$, the first term on the right-hand side vanishes; and the group torque being positive we have $\mathbf{H} s i \cos\theta = s^2 i^2 \mathbf{N} (g u_1 - j v_1)$, where u_1 and v_1 stand for the particular values of u and v when θ has fallen from the remanence value to zero. The particular value of negative extraneous force which brings about this condition is called the coercive force and is usually denoted by the symbol $\mathbf{H}_c$. Hence we find

$$\mathbf{H}_c = - s^2 i^2 \mathbf{N} (g u_1 - j v_1) \quad . \quad . \quad . \quad (4)$$

When there is no gathering together of current rings into concentrated groups, g and j are both zero, and in that case $\mathbf{H}_c$ becomes zero. Hence a magnetic material in which the magnetic molecules were distributed with absolute uniformity would have no coercive force in the ordinary sense; no ability to preserve itself in a partially oriented state as a permanent magnet. Group concentration and coercive force therefore go together, and we may infer that the greater the degree of concentration the greater will be the coercive force.

(14) The Margin of Stability and Differential Permeability.

One of the significant facts connected with highly magnetic materials like iron is the magnitude attained

by the ratio $\delta\beta/\delta\mathsf{H}$, the differential permeability as it is called. Now $\beta = k_x s i \mathsf{N} \sin\theta$, and

$$\mathsf{H} = \frac{s^2 i^2 \mathsf{N}(g u - j v) \quad (k_x - k_y) s^2 i^2 \mathsf{N} \sin\theta\cos\theta}{s i \cos\theta}$$

from which $\delta\beta/\delta\theta$ and $\delta\mathsf{H}/\delta\theta$ can be obtained.

Writing $\frac{\delta\beta}{\delta\mathsf{H}} = \frac{\delta\beta}{\delta\theta} \Big/ \frac{\delta\mathsf{H}}{\delta\theta}$ and putting $g\dot{u} - j\dot{v}$ for $g\frac{du}{d\theta} - j\frac{dv}{d\theta}$, we have:

$$\frac{\delta\beta}{\delta\mathsf{H}} = \frac{k_x \cos^2\theta}{g(\dot{u} - u\tan\theta) \quad j(\dot{v} - v\tan\theta) \quad (k_x - k_y)\cos^2\theta} \quad . \quad (5)$$

Here the denominator represents the margin of stability possessed by the mass of current rings.

On experimental grounds there is reason to believe that in a mass of which the transverse dimension is considerable compared with the size of the crystals, k_y is equal to k_x, and in the ideal case of a mass which is symmetrical in the X and Y directions, a spherical body or a cubical body for example, k_y would necessarily be equal to k_x. We may therefore assume $k_x - k_y = 0$ as a possible condition in any magnetic body; and in that case the margin of stability will vanish when g and j are both zero. In other words, if there is no gathering together of magnetic molecules into more or less separated groups, there will be no margin of positive stability, and the differential permeability of the material will be infinite.

No such material is known to us, but since in pure soft iron values of $\delta\mathsf{B}/\delta\mathsf{H}$, or what is practically the same thing $\delta\beta/\delta\mathsf{H}$, as high as 20,000 have been observed,* we infer that the molecular structure of soft iron, although not absolutely free from some kind of concentration of magnetic molecules, cannot be far from it. We may draw the further inference that the decrease in $\delta\beta/\delta\mathsf{H}$ and the increase in coercive force, which follow the introduction of carbon, for example, into iron, are the result of some departure from an almost perfect uniformity of molecular spacing in pure iron. Carbon is known to combine chemically with iron, and if the consequent molecular rearrangements involve any kind of gathering of magnetic molecules into more or less separated groups, local magnetic circuits will be established; local paths for the bonds of mutual induction which hold the magnetic molecules together as oriented local systems. And with those local bonds there comes into existence the group torque which gives a margin of stability to an otherwise unstable system of current rings. Without that margin the permanent magnet would be an impossibility.

The extreme smallness of the margin of stability in iron and steel will perhaps be realized more easily by comparing the principal positive torque acting in a piece of permanently magnetized iron, with the feeble negative applied torque which suffices to upset the balance and bring about a reduction of the orientation angle, inherent motive force, and induction, to zero. Denoting the remanent induction by β_r, and the corresponding angle by θ_r, the principal positive torque will be $\beta_r s i \cos\theta_r$. We have supposed this to be balanced partly by the tribal torque and partly by the group torque; but without considering the origin of the negative torques it is clear that in the remanence state of stable permanent magnetism there is in fact a balancing torque acting on the average current ring, equal in magnitude and opposite in sign to $\beta_r s i \cos\theta_r$, so that the positive torque is a true measure of the strength of the balanced torques acting on the average current ring. The disturbing torque due to an extraneous motive force H is $\mathsf{H} s i \cos\theta$ at the instant of its application, that is to say before the current rings have begun to turn round under its influence in the direction which diminishes θ_r. If the magnitude of the extraneously applied torque is such that in the end it just suffices to reduce θ to zero, in other words if the coercive force value is applied, then the initial value of the disturbing torque is $\mathsf{H}_c s i \cos\theta_r$ and the

TABLE I.

Comparison between the Balanced Torques of Permanently Magnetized Materials and the Disturbing Torque which destroys the Balance.

Material	Balanced Positive and Negative Torques at Remanence Point	Instantaneous Value of the resultant Positive Torque on application of H.	Instantaneous Difference between + and − Torques	
			Difference	Percentage
Annealed iron containing a small percentage of silicon	6 000	5 999·2	0·8	0·013
Annealed Lowmoor iron	8 000	7 998	2·0	0·025
Unhardened magnet steel: carbon 0·7 per cent, tungsten 5 per cent	10 200	10 171	29	0·28
The same magnet steel hardened	10 400	10 333	67	0·64

* EWING, loc. cit., p. 56.

ratio which either of the balanced torques bears to the disturbing torque will be $\beta_r si\cos\theta_r / \mathsf{H}_c si\cos\theta_r$, or simply in the proportion of β_r to H_c. Hence the remanence value of the induction, and the coercive force, may be regarded as measuring respectively the balanced torques of the remanent state, and the disturbing torque which completely destroys the balance. How great is the disparity between them will be seen from the figures given in Table I which relates to a few typical magnetic materials. In the table the torques are stated in terms of induction and applied motive force or field; they are, therefore, merely numbers proportional to the magnitude of the torques acting on the average current ring.

Although the proportion which the destroying torque bears to the inherent torques of the permanently magnetized state is unlikely to be more than a rough indication of the degree of concentration, the figures in Table I certainly suggest that in iron, and particularly in silicon iron, the departure from uniformity of molecular spacing is very slight. Even in the case of hardened tungsten magnet steel, concentration has apparently not gone very far, and may very likely be nowhere near the limit of molecular accommodation. If that surmise is correct it should not prove impossible to produce a magnetic material which, in virtue of a far higher degree of concentration in the groups of magnetic molecules, would possess a much greater coercive force than is obtained in the magnet steels now in use. But coercive force is not itself a factor of the magnetic energy which a permanent magnet is capable of maintaining, and whether a material of a higher degree of concentration would make an efficient magnet would largely depend on the current per magnetic molecule and the number of such molecules in unit volume.

(15) Interdependence of Orientation Angle, Motive Force, Induction, and Group Torques.

Equation (3), which is more of a mental aid than a strictly mathematical statement, serves to direct attention to the complexity of the conditions of equilibrium. We see that for any value of θ the motive force will have a corresponding value $\mathrm{F}_m \sin\theta$ for which there will be a corresponding induction in the X direction. But since the group torque may have any one of a number of different values, depending on the previous magnetic history of the mass of current rings, equilibrium can only be attained by giving the extraneous motive force H some particular value, governed by that of the group torque. Hence in testing a piece of iron it is found that the relative values of induction and applied motive force, the relation of β to H, depends on the previous history of the iron, and to reproduce the same value of β for any given value of H it is necessary to start from some initial standard condition, like that of the virgin iron, and subject the iron to precisely the same sequence of changes in order to secure the same group torque on arriving at the angle θ. All who are accustomed to magnetic testing are only too familiar with the fact, and the equilibrium equation points to the cause. For the same numerical relation between β and H it is not sufficient merely to give the current rings the same effective orientation angle; it is essential to build up that complicated angular state by means of identically the same deflectional conditions of the current rings in the groups, in order that the group torque may have the proper value to bring about equilibrium at the given angle θ with the given extraneous force H.

Another deduction follows immediately. Provided there is identity as regards group torque at any given angle θ, then there will be identity as regards inherent motive force and resulting induction. For example, imagine two pieces of iron A and B which are identical with respect to $si\mathsf{N}$ and the degree of concentration, and are initially in the same magnetic condition. Let both pieces be subjected to orienting forces which produce a series of angular changes, resulting in final states represented by G_a, θ_a, F_a and β_a for the piece A; and by G_b, θ_b, F_b and β_b for the piece B. Then if the sequence of angular changes has been the same for both pieces of iron, we shall have the group torques $\mathrm{G}_a = \mathrm{G}_b$ when $\theta_a = \theta_b$, and in the final states the equilibrium of torques will be identical in the two pieces. But since $\mathrm{F}_a = \mathrm{F}_m \sin\theta_a$ and $\mathrm{F}_b = \mathrm{F}_m \sin\theta_b$ it follows that when $\theta_a = \theta_b$ the inherent motive forces will also be equal, or F_a will be equal to F_b; and consequently β_a will be equal to β_b, since induction is proportional to motive force. Hence G, θ, F, and β are mutually dependent quantities and, provided the initial states and the sequences of change have been the same, there will be a final equality in group torque, equality in angle, equality in inherent motive force, and equality in flux density.

(16) Causes of Disturbance of the Equilibrium of Torques.

As we have seen, equilibrium is the result of a wonderfully elaborate and delicate balancing of mechanical forces within the mass of current rings, and its maintenance depends on each contributing factor remaining constant. Change any one of them and the balance is upset, the small margin of stability often leading to a final change in the orientation angle out of all proportion to the initiating cause of disturbance. In the present paper we are only directly concerned with two of the many possible modes of effecting a change in orientation, but a brief reference may be made to the contributory factors contained in the principal torque $\beta si\cos\theta$ and the applied torque $\mathsf{H} si\cos\theta$ due to an extraneous motive force. Beginning with the angle, although we cannot lay hold of individual current rings and turn them round on their pivotal axes, it is quite easy to jerk some of the rings round in a haphazard fashion by mechanical shocks or vibration, and in that way considerable changes in θ, and consequently in the induction, may be brought about. The same thing may be done rather more systematically by heat; and doubtless in other ways. Anything, for example, which effected a change in the geometry of the groups would give a different value to the coefficients g and j in the group torque, and the

change in the group torque would be accompanied by a change in orientation. Passing to the next factor, i, the apparent ease with which a change in the magnitude of the molecular current might be effected by electromagnetic induction was long regarded as a formidable difficulty in the way of Ampère's hypothesis. But, as Langevin has recently shown,* it would require the application of an enormously powerful magnetic field—something of the order 100,000 gauss or more—to induce a change of even one ten-thousandth part in the magnitude of the molecular current; and since the maximum flux density in iron rarely exceeds 30,000, the current with which the iron molecule is endowed is, for all practical purposes, a permanent and constant quantity. The same thing may be said of the next factor, s, for it seems probable that so long as an atom of iron, for example, preserves its character as iron, the size of the molecular circuit, the area s, must remain constant. Apart from the effect of shocks, vibration and heat, these are all matters of theoretical rather than practical importance.

There remains to consider the two factors β and $\mathbf{H}$. Since in the presence of an extraneous motive force the whole flux density is $\mathbf{B} = \beta \pm \mathbf{H}$, the principal torque will, in the general case, be $\mathbf{B} s i \cos\theta$, and it is at once evident that its value may be changed either by making a change in the magnetic conductance (or reluctance) of the magnetic circuit, or by altering the value of the extraneous motive force; two equivalent modes of changing the magnitude of the flux density on which the principal torque and therefore the equilibrium of the current rings depends. The method of predetermining the performance of permanent magnets which is described in the second part of the paper, rests on the equivalence of these two modes of bringing about a change in orientation and flux density, and we have now to determine the conditions under which they will have precisely the same effect.

(17) The Magnetic Circuit and Ohm's Law.

The two modes of changing the flux in a magnetic circuit correspond to the alternative ways of altering the current in an electric circuit by changing the resistance, or by making an addition to the electromotive force, and it will be useful to consider first the more familiar case of the electric circuit. The nearest electric analogy to the circuit of an ideal permanent magnet maintaining a magnetic flux in external space, is a battery maintaining a current in an external resistance; the point of difference to be noted here being that the inherent motive force of the magnet varies with the flux, whereas the motive force of the battery is substantially constant. Let us take the case of two identical batteries each generating an electromotive force E and each having a resistance R. In their initial condition we shall imagine them to be short-circuited, so that in each circuit the current will be $I_1 = E / R$. It will be convenient to refer to this state of things as the *self-absorbed* condition, the whole of the generated motive force being expended inside the battery in maintaining the current I_1, in the resistance R; the product $I_1 R$ being the measure of the expenditure of motive force in an inert resistance.

Now let an external inert resistance r be added to the circuit of the first battery, converting it into what may be called an *extended* circuit. The instantaneous effect of the increased resistance of the circuit is a diminution in the current and a consequent decrease in the expenditure of motive force in maintaining the diminished current in the original resistance R. Hence, after providing for the lessened expenditure out of the constant electromotive force E, there is a surplus motive force available for use elsewhere in the extended circuit, and equilibrium between the generation and expenditure of motive force is restored when the current has fallen to a value which, in effect, sets free a surplus motive force just sufficient to maintain the diminished current in the external resistance r. Denoting the final value of the diminished current by I_2 we have $I_2 = E / (R + r)$ or, if we put generated motive force on one side and expenditure on the other, $E = I_2 R + I_2 r$. The surplus motive force is numerically equal to $E - I_2 R$ of course, and denoting it by V we have $V = I_2 r$, so that $E = I_2 R + V$. The portion of the generated motive force denoted by V is commonly referred to as the terminal potential difference, but the idea of a surplus motive force will be found to lend itself better to the case of the permanent magnet.

Taking the case of the second battery, we may imagine the current to be diminished by inserting an opposing electromotive force e in the circuit, which remains in the self-absorbed condition. Denoting the diminished current by I_2 we have $I_2 = (E - e) / R$ or, if generated motive forces are put on one side and expenditure on the other, $E - e = I_2 R$, from which $E = I_2 R + e$. Comparing the final state of the two circuits we have:

$$\left.\begin{array}{ll} \text{In the extended circuit} & E = I_2 R + V \\ \text{In the self-absorbed circuit} & E = I_2 R + e \end{array}\right\} \quad . \quad (6)$$

Hence to bring about the same change in current in the two circuits, namely from I_1 to I_2, by the alternative modes, the condition to be fulfilled is that the opposing motive force applied to the self-absorbed circuit must be numerically equal to the surplus motive force set free in the extended circuit; V and e being of course opposite in sign.

The statement just made is equally true for complete magnetic circuits or flux tubes, whether they include a magnetizable material like iron or not; because on the assumption underlying Ampère's hypothesis there is only one magnetic medium to be reckoned with and in that medium there is strict proportionality between cause and effect, motive force and flux. The complexity introduced by the presence of a magnetic substance like iron has nothing to do with conducting power, the magnetic conducting power of iron in no way differing from that of air or empty space. In short, on the hypothesis of molecular currents and one universal magnetic medium, the word permeability, in so far as it implies the existence of magnetic media of different degrees of conducting power, ceases to

* *Journal de Physique*, 1905. A translation appeared in the *Electrician*, Nos. 56, 108 and 141, 1905.

have any meaning.* Nevertheless the complexity is there, but it is to be attributed to a different cause. It arises solely from the intricate conditions of equilibrium among the oriented magnetic molecules which constitute the motive force inherent in the iron; and once that equilibrium has been established, giving the iron a definite inherent motive force per unit length, the numerical relation between magnetomotive force and flux in a perfect magnetic circuit is as simple and direct as that of electromotive force and current in an electric circuit. Hence the comparison we have made between extended and self-absorbed electric circuits will hold good for magnetic circuits. There will therefore be the same numerical equality between the surplus motive force in an extended magnetic circuit and the negative motive force applied to a self-absorbed magnetic circuit (for the same change of flux density) as there is in the analogous but simpler case of electric circuits. The example given in the next section will make this clear and at the same time provide the basis for the predetermination of permanent magnets.

(18) Surplus Motive Force.

Suppose we have two complete magnetic circuits I and II, each in the form of a ring of steel of uniform sectional area. It will be assumed that the quality and condition of the steel is identically the same in the two circuits, so that the product $si\mathbf{N}$, the degree of concentration in groups, and the facilities for establishing tribal conditions with transverse induction, are the same in both cases. It is not necessary to assume identical dimensions and we shall suppose the length and sectional area of circuit I to be L and A respectively, and the corresponding dimensions of circuit II to be l and a. The reluctance of the first steel ring may be denoted by R, and that of the second by ρ; and since the medium inside the steel is assumed to be the universal magnetic medium of space, for which the conducting power is unity in its c.g.s. magnetic system, we shall have $R = L/A$ and $\rho = l/a$. To secure identity as regards their initial condition, we may imagine each ring of steel to have been fully magnetized and then allowed to settle down into the condition of stable equilibrium in which the induction in the X direction has its maximum remanent value, there being no extraneous motive force in action. In this state the orientation, inherent motive force, and induction may be denoted by θ_r, F_r, and β_r; the flux in circuit I will be $\beta_r A = F_r L/R$, and that in circuit II will be $\beta_r a = F_r l/\rho$.

Now imagine the steel ring which forms circuit I to be severed at a cross section; and that the severed ends are drawn apart so as to lengthen or extend the circuit by the addition of an air space, which since it contains no motive force constitutes an inert reluctance. Denoting the reluctance of the air space by r, the *instantaneous* effect of the increase in the reluctance of the circuit will be to diminish the flux from $\beta_r A = F_r L/R$ to $\beta A = F_r L/(R + r)$. The balance of torques having been upset in this way, the current rings will begin to turn round on their pivotal axes in a negative sense, reducing θ and consequently decreasing the motive force and bringing about a further diminution in flux. The deflectional movements among the current rings, initiated in this way, are of course accompanied by a gradual change in the group torque, and ultimately the change in the orientation angle will cease at some angle θ_1 (less that θ_r) at which equilibrium with the group torque will have been re-established. Denoting the motive force and induction by F_1 and β_1, the flux in the extended circuit in the final state of equilibrium will be $\beta_1 A = F_1 L/(R + r)$, or putting total generated motive force on one side and expenditure on the other, $F_1 L = \beta_1 AR + \beta_1 Ar$. We may imagine the generated motive force to consist of two parts, $f_1 L$ and $\phi_1 L$, of which $f_1 L$ is the motive force required to maintain the flux inside the steel, and $\phi_1 L$ is therefore the surplus motive force which is expended in maintaining the flux in the external reluctance r. We shall then have $f_1 L = \beta_1 AR$ and $\phi_1 L = \beta_1 Ar$, from which $f_1 = \beta_1 (A/L) R = \beta_1$, and $\phi_1 = \beta_1 Ar/L$. The quantity f_1 is the motive force per cm. of steel which is utilized inside the steel and is, of course, numerically equal to the induction. The quantity ϕ_1 is the surplus motive force per cm. of steel, which, not being used inside the steel, becomes available for use outside and is actually expended in the external inert reluctance. We may now write the equation of motive forces per cm. in the first circuit in the form $F_1 = f_1 + \phi_1$, or since f_1 is numerically equal to β_1, we shall have the numerical relation:

$$F_1 = \beta_1 + \phi_1 \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

Now consider the case of the second circuit of steel in which the induction is to be reduced by an extraneous motive force applied in the negative direction, the circuit remaining in the self-absorbed state. For this purpose we may imagine a coil to be wound uniformly round the steel ring so that a current in the coil will create a uniform extraneous motive force. Denoting the extraneous force per cm. by $\mathbf{H}$, the *instantaneous* effect of its application will be to diminish the motive force acting in the circuit from $F_r l$ to $(F_r - \mathbf{H}) l$. The instantaneous decrease in the induction and principal positive torque will initiate turning movements among the current rings in precisely the same way as the decrease in induction caused by adding reluctance to the first circuit, and the induction will continue to fall in value until equilibrium is ultimately re-established by the concurrent change in the group torque. The orientation angle and motive force in circuit II in the final state of equilibrium may be denoted by θ_2 and F_2 respectively. The flux in the final state is not created solely by the inherent motive force, and to mark the distinction the final flux density may be denoted by $\mathbf{B}$, which is arithmetically the same thing as the difference $\beta_2 - \mathbf{H}$. The flux in the self-absorbed circuit will now be $\mathbf{B}a = (F_2 - \mathbf{H}) l/\rho$ and, since $\rho = l/a$, this

* The word "permeability" in this connection was introduced some 60 years ago by W. Thomson (Lord Kelvin). Less happily chosen than Faraday's "induction," it suggests that magnetism is forced through a piece of iron in much the same way as water under hydraulic pressure goes through a permeable body like sandstone, and its continued use has rather tended to withdraw attention from the essence of the phenomena.

reduces to the simple form $\mathbf{B} = F_2 - \mathbf{H}$, so that in the case of the self-absorbed circuit we have:

$$F_2 = \mathbf{B} - \mathbf{H} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

In their final states of equilibrium, therefore, the two magnetic circuits compare as follows:

$$\left.\begin{array}{l} \text{In the extended circuit} \quad F_1 = \beta_1 + \phi_1 \\ \text{In the self-absorbed circuit} \quad F_2 = \mathbf{B} + \mathbf{H} \end{array}\right\} \quad . \quad (9)$$

This comparison is on all fours with that already made [see Formula (6)] between two electric circuits under similar conditions, remembering that in the electric case we were dealing with total motive forces, whereas in the case of magnetic circuits the corresponding quantities are motive forces per cm. of steel.

Now suppose the magnitude of $\mathbf{H}$ has been so chosen that in the final state of the two circuits the flux density $\mathbf{B}$ in the second circuit is equal to the induction β_1 in the first circuit. The initial states having been identical and the sequence of change alike in both circuits, resulting in flux densities of the same value and consequently identical values for the principal torque, there will be equality between the remaining dependent quantities, and hence when $\mathbf{B}$ has been made equal to β_1 by giving $\mathbf{H}$ the appropriate value, we shall have $\theta_2 = \theta_1$, and consequently F_2 will be equal to F_1. Hence the equation for the self-absorbed circuit, namely $F_2 = \mathbf{B} - \mathbf{H}$, becomes $F_1 = \beta_1 - \mathbf{H}_2$, where $\mathbf{H}_2$ stands for the particular value of $\mathbf{H}$ which makes the final flux densities equal.

We find, then, that when the flux density in the two circuits has been reduced from the same initial value to the same final value by the two modes of effecting the change, the comparison between the magnetic circuits in their final condition of equilibrium becomes:

$$\left.\begin{array}{l} \text{For the extended circuit} \quad F_1 = \beta_1 + \phi_1 \\ \text{For the self-absorbed circuit} \quad F_1 = \beta_1 + \mathbf{H}_2 \end{array}\right\} \quad . \quad (10)$$

and hence, numerically,

$$\phi_1 = \mathbf{H}_2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

Notwithstanding the complicated conditions of equilibrium in a mass of current rings the ultimate relation between the two magnetic circuits is precisely analogous to that of the extended and self-absorbed electric circuits, and for equivalence of change in the magnetic case the condition is that the positive surplus motive force per cm. of steel in the extended circuit shall be numerically equal to the negative extraneous motive force, per cm. of steel, applied to the self-absorbed circuit.

In the foregoing demonstration of the numerical equality of ϕ_1 and $\mathbf{H}_2$, we have endeavoured to trace the reason for that equality to its origin in the equilibrium of current rings and to form some sort of mental picture of the actions on which equivalence of effect ultimately depends. A proof, much more compact to the eye, may be obtained by importing the mathematical conception of potential, provided we are content to ignore what is going on inside the steel.

(19) Molecular Currents, Equivalent Current and Intensity of Magnetization.

The effective motive force of a mass of current rings does not differ in its nature from that of a current flowing in a coil, and a useful comparison may be made between two magnetic circuits of identical dimensions and therefore identical reluctance, which differ solely in the origin of their magnetomotive force; one having the inherent motive force of some magnetic substance, and the other the extraneous motive force applied by a coil. By way of example we will take a closed ring of iron to represent the first case, and a closed ring of wood (or some inert substance of the kind) wound with a uniformly spaced coil of wire to represent the second. For simplicity we shall suppose the coil to have one turn per cm., so that the extraneous motive force will be $4\pi\mathrm{I}$ per cm. In the iron circuit the inherent motive force when the current rings are oriented to angle θ will be $F_\theta = 4\pi si\mathbf{N}\sin\theta$. If the current in the coil is so adjusted as to make the flux density in the wooden ring equal to that in the iron ring we shall have $4\pi\mathrm{I}_\theta = 4\pi si\mathbf{N}\sin\theta$, where I_θ denotes the adjusted current. Hence:

$$\mathrm{I}_\theta = si\mathbf{N}\sin\theta \quad . \quad . \quad . \quad . \quad . \quad (12)$$

The magnetic medium being assumed to be the same in both circuits, and the dimensions being identical, when the motive forces have been made equal by adjusting the current, the flux in the wooden ring will be equal to that in the iron ring. The adjusted current is therefore equivalent in effect to the aggregate molecular current in the oriented iron and we may define I_θ as the "equivalent current" of a magnetic material oriented to angle θ.

When the magnetic material is magnetized to the utmost extent so that θ is as nearly as may be 90° and $\sin\theta$ becomes unity, the inherent motive force attains its maximum value, namely $si\mathbf{N}$. Denoting the equivalent current corresponding with this state of things by I_m we have:

$$\mathrm{I}_m = si\mathbf{N} \quad . \quad . \quad . \quad . \quad . \quad . \quad (13)$$

and I_m may be referred to as the maximum equivalent current.

The product si is the area of a circuit into the current, a quantity which is defined as the magnetic moment of the circuit, because that is the turning moment or torque which it would experience if placed in a magnetic field of unit strength with the plane of the circuit parallel with the direction of the field. The magnetic moment of each current ring is therefore si, and since $\mathbf{N}$ is the number of current rings in a cubic cm. the quantity $si\mathbf{N}$ is the aggregate magnetic moment of the mass of completely oriented current rings contained in a cubic cm. But magnetic moment per cubic cm. is the quantity known as "intensity of magnetization," and hence if we denote the maximum intensity by J_m we shall have $\mathrm{J}_m = si\mathbf{N}$ for any magnetizable material magnetized to the utmost extent. We find therefore that:

$$\left.\begin{array}{l} \text{Maximum equivalent current} \quad \mathrm{I}_m = si\mathbf{N} \\ \text{Maximum intensity of magnetization} \quad \mathrm{J}_m = si\mathbf{N} \end{array}\right\} \quad . \quad (14)$$

" Equivalent current " and " intensity of magnetization " are therefore merely two ways of expressing the same quantity, namely the aggregate effective molecular current in a cubic cm. of any magnetizable substance in an oriented state. Like so many other terms in magnetism, intensity of magnetization has its roots in imaginary magnetic matter. By stating the quantity it stands for in terms of an electric current, we bring it into line with Ampère's hypothesis and obtain a direct comparison between quantities of the same kind, the current in the molecules and the particular current in the hypothetical coil which would have the same magnetic effect.*

(20) The Maximum Equivalent Current in Iron Accounted for by Electrons Moving in Atomic Orbits.

Ewing has demonstrated by means of his " isthmus method " that the induction created by the inherent magnetomotive forces of iron cannot be increased beyond a maximum of about 21,500 lines per square cm. no matter how powerful the applied orienting torque may be.† The maximum induction is numerically equal to the maximum inherent motive force per cm., namely $4\pi si\mathbf{N}$; or $4\pi I_m$, since $si\mathbf{N}$ is the maximum equivalent current. Hence in iron $4\pi I_m = 21{,}500$, and the experimental value of I_m is therefore $21{,}500/4\pi$ or about 1,700. That is to say the maximum equivalent current in iron is about 1,700 c.g.s. magnetic units, or 17,000 amperes, per cm. of length measured in the direction of the induction. This figure has been confirmed by Du Bois, who used a method of measurement depending on the rotation of polarized light by a magnetic field. Stated in familiar terms the natural magnetizing coils inside iron, when completely oriented, provide a magnetizing force of 17,000 ampere-turns per cm., a figure which enables us to realize the enormous magnetomotive force which Nature gives us ready made in every piece of iron.

The question naturally arises whether such a figure as that just given for the maximum equivalent current in iron is compatible with what is known or conjectured about electronic atoms; whether any reasonably probable number of electrons per molecule moving at any likely speed in orbits of atomic dimensions, and constituting Ampère's molecular current, would in the aggregate be equivalent to 17,000 amperes per cm. At this point therefore it will be useful to make some sort of tentative comparison between the two, although it can be little more than a guess at the size of orbit and the electron velocity which would account for the observed magnitude of the equivalent current.

The equation to be solved is $si\mathbf{N} = 17{,}000$ amperes. If an electron makes n revolutions per second round its orbit, it is equivalent to a current en, where e is the electron charge; and if there are x electrons per molecule revolving in the same direction, the current per molecule will be $i = enx$. The equation therefore becomes $senx\mathbf{N} = 17{,}000$ amperes. We may take Millikan's value for e, namely $4{\cdot}77/10^{10}$ electrostatic units, and since there are 3×10^9 electrostatic units in a coulomb we shall have $e = 1{\cdot}6/10^{19}$ coulombs. $\mathbf{N}$ is the number of magnetic molecules in a cubic cm. of iron, and if we assume all the molecules to be of the magnetic type, $\mathbf{N}$ may be deduced from what is sometimes called the " diameter " of a molecule, by which is meant the diameter of the space monopolized by the molecule. Judging from experiments on gases the average distance between the centres of contiguous molecules in a solid body is about $3/10^8$ cm., a dimension which may be denoted by d. The number of molecules per cubic cm. will be $1/d^3$, that is to say the reciprocal of $27/10^{24}$, so that $\mathbf{N}$ is about 37×10^{21}. It does not appear that any definite conclusion has been reached as to the actual number of electrons in an atom, although it is known to be proportional, or nearly so, to the atomic weight of the substance. We shall proceed on the assumption that the number cannot be less than half the atomic weight, and taking the atomic weight of iron as 56 the iron atom will contain not less than 28 electrons and for the molecule of two atoms we shall have $x = 56$. It is only possible to make a guess at the area of the average electron orbit.* Obviously its diameter must be less than d, the distance between the centres of contiguous molecules, and it seems probable that it is small compared with that distance. We shall assume the diameter to be $d/10$ which makes $s = 7/10^{18}$ sq. cm. Having assigned values to all the quantities except n, the equation becomes $n = 17{,}000/(sex\mathbf{N})$, from which:

$$n = \frac{17{,}000 \times 10^{18} \times 10^{19}}{7 \cdot 1{\cdot}6 \times 56 \cdot 37 \times 10^{21}}$$

so that n is about 7×10^{15} revolutions per second. The assumption that the radius of the orbit is about one-tenth of $3/10^8$ makes the perimeter about $9/10^9$ cm. Hence the electrons would have a velocity of the order $7\times10^{15}\times9/10^9$ or 6×10^7 cm. per second; a speed which agrees well enough with what is known about electronic velocities, being several hundred times less than the velocity of light.

The object of a comparison of this kind, founded on conjectural values, is to give some kind of sense of proportion. However precarious the data may be, it is sufficient for our present purpose to know that the electrons present in each molecule of iron, moving in orbits of atomic dimensions, at a speed well within the region of electronic velocities, will fully account for the magnetomotive force inherent in iron, deduced from the observed value of the maximum equivalent current; namely 17,000 amperes per cm. Enough is already known, then, to convert Ampère's happy guess at a molecular current into a reality, and with more precise knowledge of the electron and the atom

* In early days when physicists occupied so much of their time in measuring the horizontal component of the earth's magnetic field by means of a permanent magnet, "magnetic moment" was naturally the most important quantity belonging to a magnet. But in the industrial applications of permanent magnetism, magnetic moment is of little or no importance, because the turning moment exerted on a magnet by a magnetic field does not usually tell us what we want to know.

† Ewing, loc. cit., Chap. VII.

* For an estimate of the size of electron orbits, based on the Rutherford atom with its nucleus of positive electricity, the reader is referred to a paper by N. Bohr (*Philosophical Magazine*, July 1913). The same Number contains a widely different estimate by A. C. Crehore founded on the atomic structure proposed by Sir J. J. Thomson, in which the electrons move in orbits inside the positive electricity embodied in the atom. The size assumed in the text is of the same order of magnitude as that deduced by Bohr.

the mere arithmetic of the matter cannot fail to come right.

Naturally a theory which begins with an electron running round an atomic orbit must at the present time bristle with difficulties. But the substantial truth of Ampère's hypothesis no longer admits of doubt; and with Ewing's theory of the interactions between the magnetic molecules, amplified by tracing the stability of the oriented system to local mutual induction, we are able to follow the working of the magnetic mechanism inside a permanent magnet. The interplay of attractions and repulsions among the elementary circuits is, as we have seen, an extraordinarily complicated business and much remains obscure; but at all events we are no longer groping entirely in the dark.

To sum up the whole matter in the words of one whose prophetic vision has been a fruitful source of inspiration and discovery for half a century: "according to Ampère's hypothesis the properties of what we call magnetized matter are due to molecular currents, so that it is only when we regard the substance in large masses that our theory of magnetization is applicable, and if our mathematical methods are supposed capable of taking into account what goes on within individual molecules they will discover nothing but electric circuits." *

PART II.

DESIGN AND PREDETERMINATION OF PERMANENT MAGNETS.

(21) The Magnetic Energy which a Permanent Magnet is required to Maintain.

Turning now from what is going on inside the magnet, a subject which will always call for the exercise of imagination, to the useful effect outside, which must be treated in practice as a matter of arithmetic, we shall find that the fundamental equations of the permanent magnet can be deduced directly from the principle of equivalence explained in Sections (17) and (18). The negative portion of the cyclic curve, obtained in the ordinary way from a sample of steel, gives the relation between the extraneous motive force applied in the negative direction and the flux density, in a self-absorbed circuit; and on the principle of equivalence, the negative force so applied is numerically equal to the surplus motive force which will be available for use outside a magnet made from the same kind of steel as the sample.

The development and application of the working equations will be readily understood if the practical end of the problem is borne in mind. The useful function of a magnet is, in general terms, to magnetize some piece of apparatus in which magnetism plays a part; or more precisely, to maintain magnetic energy in some particular space where it is desired to have a magnetic flux or field. To do this the magnet is called upon to maintain not only the energy corresponding with the flux we intend to utilize, but also that corresponding with the leakage flux which unavoidably extends throughout surrounding space.

The total quantity of energy which the magnet will be required to maintain is not difficult to estimate when the arrangements and dimensions of the apparatus to be magnetized have been settled. To take a simple case, let us suppose that the magnetic components of some piece of apparatus consist of two soft iron pole-pieces, such as those shown in Fig. 5, and that the requirement is a magnetic field of strength H in the air-gap between their two adjacent sides. The magnetic energy in a unit volume of air space where the field strength is H is $H^2/(8\pi)$, and denoting the area of the air space by S and the distance between the opposite faces of the pole-pieces, or width of gap, by g, the whole energy to be maintained in the gap will be $H^2Sg/(8\pi)$. If, for simplicity, we measure magnetic energy in small units of which 8π, or about 25, go to the erg, then the useful energy will be H^2Sg which may be written $HS.Hg$. But HS is the total flux in the gap and Hg is the magnetomotive force or magnetic potential difference required to maintain it. Hence, if the useful flux is denoted by B_u and the potential difference by V we shall have $HS = B_u$ and $Hg = V$, and the useful energy to be maintained will be B_uV.

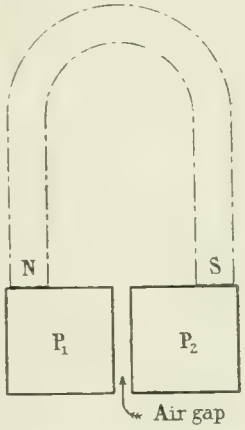


Fig. 5.—Typical apparatus of pole-pieces and air-gap; to be magnetized by a permanent magnet.

The energy maintained in the gap, or in any other space, may of course be expressed in terms of either reluctance or magnetic conductance. It will be convenient in most cases to use the latter term, because the flux in any apparatus traverses paths which are, more often than not, in parallel, and the arithmetic of the problem is much facilitated when leakage paths may be combined by simple addition. If the conductance of the air-gap is denoted by k_u we shall have $B_u = k_uV$, and similarly, if k_p denotes the sum of the conductances of all leakage paths extending through surrounding space from one pole-piece to the other, the total leakage flux will be k_pV. Here and elsewhere the assumption is made that the surfaces

* Clerk Maxwell: "Electricity and Magnetism," vol. 2, art. 615. In this and many another passage, Maxwell seems to imply that mathematical methods and mental insight are all one, as indeed they were to him

of the pole-pieces may be treated as equipotential surfaces; so that the potential difference is the same for all leakage paths. This is justified in practice, provided the flux density in the pole-pieces does not exceed a few thousand lines; because so long as the density in them is less than the remanence value for the material of which they are made, the natural motive forces inherent in the pole-pieces themselves will be more than enough to maintain the flux in them. Adding the useful flux and leakage flux, the entire energy to be maintained in the apparatus will be $(B_u + B_p)V = BV$, where B stands for the total flux which must traverse the apparatus in order to provide the required useful flux or field. This, then, is the estimated amount of the magnetic energy which the proposed magnet (indicated by dotted lines in Fig. 5) will be called on to maintain. To import the convenient phraseology of the analogous electric circuit, the magnet must deliver to the pole-pieces a terminal flux B at a terminal potential difference V and the product BV will be the energy output of the magnet, apart from leakage from the surfaces of the magnet itself.

Knowing the two factors of the energy requirement, the problem of the designer is to find the dimensions of a permanent magnet which will maintain the required flux at the estimated potential difference. Apart from leakage from the surfaces of the magnet the solution of the problem is of the simplest kind; but when magnet leakage is taken into account, as it must be in all practical cases, the dimensions of the magnet can only be arrived at after one or two approximations. The converse problem, the problem of predetermination, or forecasting the output of a magnet, that is to say, the amount of energy which a magnet of given dimensions will be capable of maintaining, can always be solved; and it will be found that in all ordinary cases reasonable accuracy of predetermination does not require more than rough estimates of the conductance of leakage paths.

The methods to be adopted in estimating the total magnetic requirement BV of any piece of apparatus which is to be magnetized by a permanent magnet, do not differ from those in general use for predetermining the flux and magnetic potential difference between the poles of dynamos and motors, and they will not be entered on in detail.* We shall confine ourselves mainly to the problem of the permanent magnet regarded as the source from which the required energy is to be obtained, and in what follows it will be assumed that the values of the two factors B and V of the energy requirement are known.

(22) The Demagnetization Curve as the Basis for Design and Predetermination.

The first step towards a forecast of the performance of a magnet is to obtain the demagnetization curve of the steel from which the magnet is to be made. It will be assumed that a hardened test-piece has been prepared from a sample of the steel, fairly representative of the bulk, and that, by one or other of the methods of testing in common use, a number of corresponding values of applied motive force and flux density have been observed; from which the demagnetizing or negative portion of the cyclic **B-H** curve has been drawn. To secure standard conditions in the usual way, the required part of the curve will have been obtained in the course of carrying the test-piece through a maximum cycle, and the negative curve will therefore correspond to the conditions in a magnet which has been fully magnetized. In this way, the necessary identity in the sequence of changes in orientation in test-piece and magnet is effectively obtained, without the necessity for any precautions other than those commonly observed in testing magnetic materials.

Naturally, data obtained under such conditions result in a forecast of what the magnet would do when in the fully magnetized state. Magnets are, however, seldom used in that condition, and the figures taken

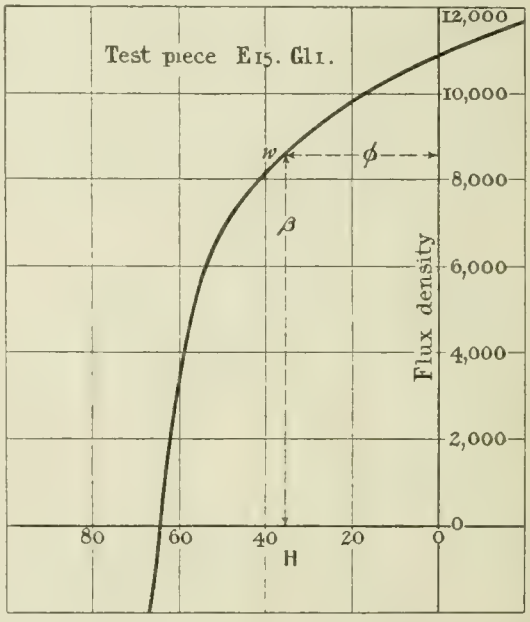


Fig. 6.—Typical demagnetization curve for tungsten magnet steel. The co-ordinates are **H**, the extraneously applied motive force per cm. of steel, and **B**, the flux density in the steel. The surplus motive force, ϕ, is numerically equal to **H**.

for the required terminal flux and potential difference must therefore include an allowance for the intended difference between the maximum and the working strength of the magnet. The percentage reduction in strength which it is desirable to make depends on the anticipated circumstances of use, and the amount to be allowed for is a matter for the designer to settle beforehand. In what follows, therefore, it is the gross energy requirement which is taken as the basis for both design and predetermination; so that when the finished magnet, after being fully magnetized, has been intentionally reduced in strength by the given percentage, it will fulfil the actual net requirement.

A typical demagnetization curve is shown in Fig. 6 for hardened tungsten-carbon magnet steel. The curve

* Several useful formulæ for estimating magnetic conductances will be found in an Appendix.

represents the relation between an extraneous motive force **H**, applied in the negative direction, and the positive flux density **B**, in a magnetic circuit which is in what we have referred to as the self-absorbed state; that is to say the state when the resultant motive force (namely, that inherent in the oriented steel, less the extraneously applied negative force) is expended in maintaining the flux in the steel. Now, since the function of a magnet is to maintain a flux in some portion of space outside the steel, the magnetic circuit of a useful magnet must necessarily be what we have defined as an extended circuit. Hence, the negative force **H** corresponding with any flux density **B**, at any point *w* for example, on the curve in Fig. 6, will be numerically equal to the surplus motive force ϕ created by the steel at any point inside the magnet where the induction β is equal to **B**. The demagnetization curve therefore represents two equivalent laws, namely the relation between **H** and **B** in a self-absorbed circuit, and that between ϕ and β in the extended circuit of a permanent magnet. To be pedantically correct, the β-ϕ curve should be drawn on the right-hand side of the vertical axis, surplus motive force being a positive quantity; but in practice the magnitude of ϕ at any density is ascertained by reading the value of **H** at the same density on the **B**-**H** curve without troubling about the difference in sign between ϕ and **H**.

(23) The Fundamental Equations for an Ideal Permanent Magnet. Energy Equation, and Ratio Equation.

It is customary to supply magnet steel in rolled bars, and hence in practice the sectional area of a magnet is constant along its length. Leakage from one limb of the magnet to the other * being unavoidable, a constant sectional area involves a variation in flux density from a maximum at the "neutral section" to a minimum at the ends of the magnet. Before dealing with the difficulties which arise from varying density, the fundamental equations must be derived from a consideration of the simpler case of ideal magnets in which the flux density in the steel is uniform. In an ideal magnet the limbs have a gradually decreasing sectional area from the neutral section to the ends; and the rate of decrease in area being made equal to the rate at which the flux decreases by reason of the leakage from limb to limb, the flux density in the steel is uniform. Magnets of this kind utilize the steel to the best advantage, but until it becomes possible to make permanent magnets in the form of magnet-steel castings, so as to permit the sectional area to be varied appropriately, the magnet of uniform density must be regarded as an ideal type.

We shall begin by considering two magnets of uniform density, the first being a bent magnet like that shown in Fig. 7 and used in conjunction with two pole-pieces for maintaining a magnetic field in an air-gap. The flux density being uniform, the lines of induction in the steel will everywhere lie parallel with the magnetic axis of the magnet. We may therefore regard an ideal magnet as consisting of two parts having distinct functions; a central core of uniform cross section (indicated by dotted lines in Fig. 7) which serves to carry the flux delivered to the pole-pieces; and an enveloping tubular portion of gradually decreasing sectional area, which serves to carry the leakage flux passing from one limb to the other; the tubular part enclosing the core and forming what may be called a leakage sleeve. Since the flux density is uniform, all lines of induction are parallel with the magnetic axis and no induction will pass to and fro between the sleeve and the core. The two might therefore be separate pieces of steel without in any way affecting the behaviour of the magnet.

Regarding the core and the leakage sleeve of the magnet in Fig. 7 as entirely distinct members, attention may now be concentrated on the core, which forms a tube of flux of uniform sectional area from one

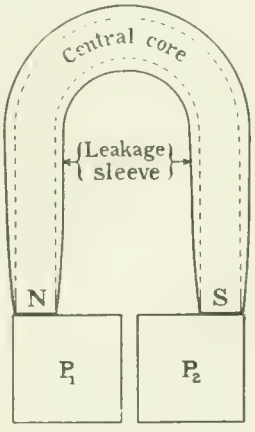


Fig. 7.—Ideal permanent magnet of uniform flux density; showing the central core of uniform sectional area, carrying the useful flux, surrounded by a sleeve carrying the leakage flux.

end of the magnet to the other. Denoting the length and sectional area of the core by L and A respectively, the equations between the two factors of the required energy BV and the dimensions of the magnet will be:

$$B = \beta A \quad \text{and} \quad V = \phi L \quad . \quad . \quad . \quad . \quad (15)$$

From these two primitive equations, it is evident that to provide the required energy we might choose at random any flux density β_1 (less than the remanence value, of course) and by making $A = B/\beta_1$, the core would deliver the required terminal flux. Also, if ϕ_1 stands for the surplus motive force of the steel when the density is β_1 we have only to make $L = V/\phi_1$ in order to provide the required terminal potential difference. For example, by choosing a flux density closely approaching the remanence value, the sectional area of the core will have a minimum value; but since ϕ would in that case be indefinitely small (see Fig. 6) the length of the core would be indefinitely great. At the other end of the range of possible dimensions, we should find the converse conditions; the flux density

* It is convenient to regard every magnet, whatever its shape, as being divided into two limbs, one on each side of that section which forms the magnetic centre of the magnet. The magnetic centre, which is usually but not invariably located at the geometric centre, is referred to in the text as the "neutral section."

being indefinitely small, the area of the core must be indefinitely large, while the surplus force would reach its maximum possible value; that is to say, it would approach the coercive force H_c in magnitude. In between these extreme cases any number of magnet cores might be made on the basis of the primitive equations, of different proportions and containing widely different volumes of steel, and each would deliver the required terminal flux at the required terminal potential difference. Hence, if the volume of steel used for any given requirement is a matter of indifference, a random choice of dimensions will serve.* But if economy of steel is aimed at or, what is often of more importance, economy of space occupied by the magnet, then something more than haphazard design is needed; minimum volume of steel for the given energy requirement must be the primary condition of design.

understood that the steel has been brought to the given flux density by extending the magnetic circuit so as to cause some of the inherent magnetomotive force of the steel to be expended in the inert reluctance of external space.

Since L A is the volume of steel in the magnet core, equation (16) may be written in the form:

$$\text{Volume of steel in magnet core} = \frac{BV}{\beta\phi} \quad . \quad (18)$$

from which it is evident that if our object is to use the smallest volume of steel which will suffice to provide for the given energy requirement, the flux density must be so chosen as to give the product $\beta\phi$ the maximum possible value. That such a maximum exists is obvious from the shape of the demagnetization curve, and it is easily found by reckoning the product $\beta\phi$, or what

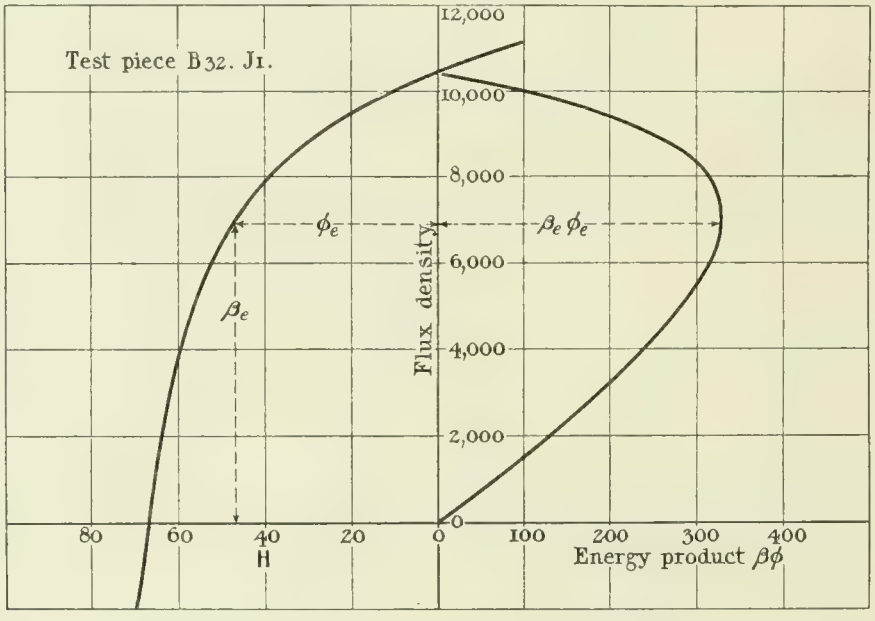


FIG. 8.—Typical demagnetization curve for magnet steel, showing the derived curve of the energy product $\beta\phi$.

Numbers on the energy scale when multiplied by 1,000 8π give the energy in ergs.

The necessary condition for economy of steel will be apparent if the two factors of the energy requirement are taken into account simultaneously by multiplying the two primitive equations (15) together. In this way we obtain the first of the two fundamental equations of the permanent magnet, the Energy Equation:

$$BV = \beta\phi L A \quad . \quad . \quad . \quad . \quad . \quad . \quad (16)$$

Here BV is the amount of energy maintained in external space by a volume of steel L A in which the flux density has the value β. For unit volume of steel, or L A = 1 cubic cm., we shall have:

$$\left.\begin{array}{l}\text{External energy maintained by}\\ \text{1 cubic cm. of steel at flux density } \beta\end{array}\right\} = \beta\phi \quad . \quad (17)$$

The product $\beta\phi$ is therefore the available or useful energy per cubic cm. of magnetized steel; it being

comes to the same thing, B H, for a number of corresponding co-ordinates of the demagnetization curve, and plotting them as points on a derived curve connecting betaphi with either β or ϕ.* To avoid a confusion of curves, it is generally more convenient to plot $\beta\phi$ against β, so that the betaphi curve may be drawn on the right-hand side of the density axis of the demagnetization curve, as shown in Fig. 8. In this way the particular value of the flux density corresponding with the maximum value of $\beta\phi$, that is to say, the "economic density," is seen at a glance, and the corresponding magnitude of the surplus motive force is also ascertained at once by inspection.

Denoting the economic density by β_e and the corresponding surplus force by ϕ_e, the economic dimensions

* The long survival of rule-of-thumb design, or no design at all, is no doubt partly owing to the ease with which the wrong magnet may be made to answer the purpose. The waste of steel has been unconscious.

* The author first began plotting $\beta\phi$ curves 18 years ago in order to judge the quality of magnet steels by maximum value of product. Three years later, the product curve was first applied in a tentative fashion to the design of a permanent magnet. The natural difficulties of the subject greatly retarded development, and it is only within the past five years that the method has settled down into a regular routine.

of the magnet core can now be determined by inserting these particular values in the primitive equations. Thus we shall have :

$$A_e = \frac{B}{\beta_e} \text{ and } L_e = \frac{V}{\phi_e} \quad . \quad . \quad . \quad . \quad . \quad (19)$$

$A_e L_e$ being the smallest volume of steel, of the quality represented by the demagnetization curve, which will maintain the external energy BV.

Magnets of uniform density being for the present a somewhat impracticable form, the process by which the dimensions of the leakage sleeve are arrived at need not be entered into here in detail. It may be mentioned, however, that the outline of the sleeve, or growth in its sectional area, may be determined with sufficient accuracy by making step-by-step additions to the area, the procedure being much the same as the double step-by-step integration which will be described in a later section. Assuming the correct outline has been given to the leakage sleeve, the flux density and surplus motive force will be β_e and ϕ_e in the sleeve as in the magnet core, and hence the magnetic energy in the leakage field which extends from one magnet limb to the other will be $\beta_e \phi_e \times$ volume of sleeve. Adding this to the useful energy, the total magnetic energy maintained by the magnet, in space external to itself, will be $\beta_e \phi_e \times$ total volume of magnet. Although the relation between $\beta\phi$ and external energy only applies in this simple form to ideal magnets of uniform flux density, the same principle holds for ordinary magnets of uniform sectional area and varying flux density.

The converse problem of predetermining the useful energy which a magnet of given dimensions will maintain in external space must now be considered. Returning to the primitive equations (15), if we divide one by the other we shall obtain the second fundamental equation of the permanent magnet, the Ratio Equation :

$$\frac{B}{V} = \frac{\beta A}{\phi L}, \text{ or } \frac{\beta}{\phi} = \frac{L}{A} \cdot \frac{B}{V}$$

The ratio B/V is of course numerically the same as the total or terminal conductance of the apparatus ; namely the sum of the conductances of the air gap and the leakage paths from one pole-piece to the other. Denoting their sum by $k_u + k_p$ and putting $B/V = k_u + k_p$ the ratio equation becomes :

$$\frac{\beta}{\phi} = \frac{L}{A}(k_u + k_p) \quad . \quad . \quad . \quad . \quad . \quad (20)$$

this being the most convenient form of the equation for the purpose of forecasting what a magnet will do. For any given magnet core, L and A are known ; and for any given piece of apparatus (pole-pieces or what not) the conductances k_u and k_p can be estimated. All the quantities on the right-hand side being known, the ratio equation gives a particular ratio β_1/ϕ_1, and to forecast the terminal flux and potential difference it is only necessary to find a point on the β-ϕ curve where the co-ordinates stand in that ratio to each other. Having ascertained the separate values β_1 and ϕ_1 in this way, they have only to be inserted in the primitive equation to determine the values of terminal flux and potential difference ; thus :

$$B = \beta_1 A \text{ and } V = \phi_1 L \quad . \quad . \quad . \quad (21)$$

In the next section, it will be seen that although the ratio equation is only strictly true for magnets of uniform flux density, it may be applied in a modified form to the case of ordinary magnets and provides a ready means for finding out approximately what any magnet will do ; the application of the ratio equation

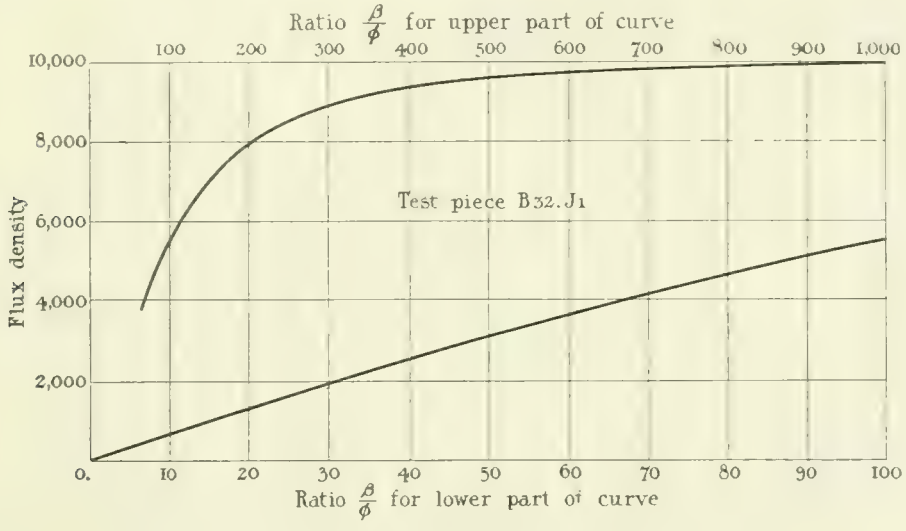


FIG. 9.—Curve derived from demagnetization curve, Fig. 8, showing the relation between the ratio β/ϕ and the flux density β.

in many cases avoiding recourse to the more laborious method of step-by-step integration.

In making use of the ratio equation, the task of finding the particular point on the demagnetization curve where the co-ordinates have the required ratio, is made easy by drawing a derived curve, like that shown in Fig. 9, connecting the ratio β/ϕ with the flux density β. Data for this second derived curve are easily obtained by reckoning the value of the ratio β/ϕ for a number of points on the demagnetization curve. It is often useful to have at hand a third derived curve like that given in Fig. 10, expressing the relation between the ratio β/ϕ and the surplus force ϕ, from which the terminal potential difference may be ascertained at once.

Although equation (20) states the ratio equation in the form most generally convenient for practical use, it will be instructive to express it in another way. The quantity L/A is the reluctance of the space occupied by the magnet core; in other words it is the reluctance of that part of the magnetic circuit or flux tube which contains the magnetomotive force. Again, the terminal conductance $k_u + k_p$ is the reciprocal of the reluctance of that part of the magnetic circuit which lies outside the motive force region; that is to say the reciprocal of the inert reluctance of the space external to the magnet core. Hence, denoting $1/(k_u + k_p)$ by r and L/A by R, the ratio equation reduces to:

$$\frac{\beta}{\phi} = \frac{R}{r}; \quad . \quad . \quad . \quad . \quad . \quad . \quad (22)$$

a form which expresses the connection of the ratio β/ϕ with the proportions between the two parts of a perfect magnetic circuit or flux tube in the simplest possible way. To interpret the equation in a physical sense β must be replaced by f, the motive force expended in the steel, per cm., which is numerically equal to the induction. We than have $f/\phi = R/r$, or the ratio of motive forces expended inside and outside the steel is equal to the ratio of internal and external reluctances.

(24) Bar Magnet of Uniform Flux Density. (Ellipsoid Magnet.)

Our second example of a magnet of uniform flux density is one of an academic type, the ellipsoid magnet being of little or no importance outside the laboratory. But it will be useful to consider it here, because one or two deductions of general utility may be drawn from it and applied in practice to ordinary magnets.

The shape to be given to a magnet in order to obtain uniform flux density becomes a mathematical problem when the magnetic axis of the magnet is a straight line; the general solution, founded on a theorem due to Poisson, was obtained long ago, and is to be found in the textbooks.* It was derived from the gravitation potential of a body of the same shape as the magnet, and is therefore naturally expressed in the language of imaginary magnetic attractive matter. To translate the general solution into terms of motive force, reluctance and flux, is unnecessary for the present purpose, and it will conform better with the ideas on which this paper is founded if we ascertain the shape which must be given the magnet in order to secure uniform flux density, by treating it as a system of elementary magnetic circuits.

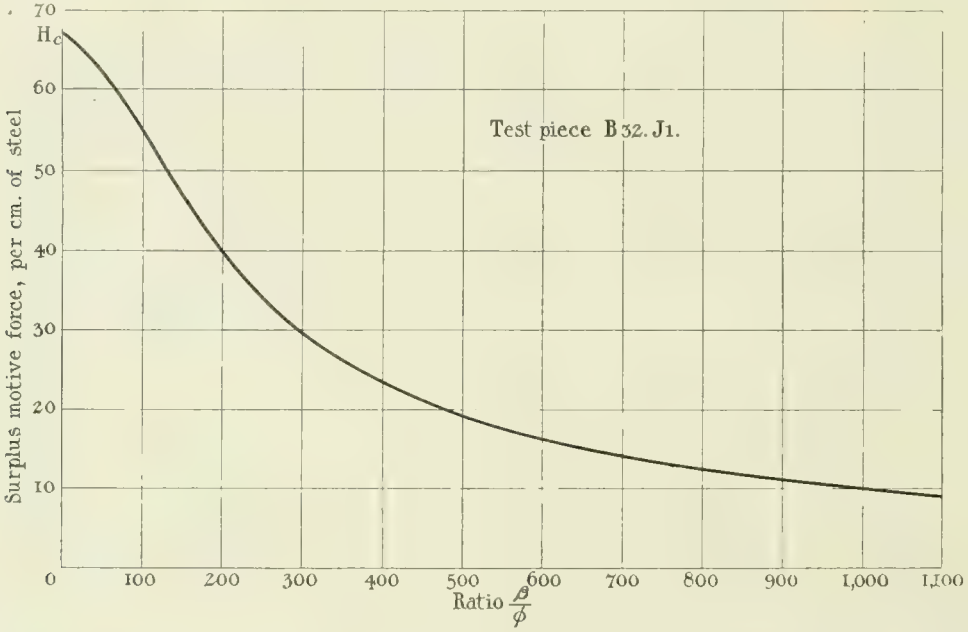


Fig. 10.—Curve derived from demagnetization curve, Fig. 8, showing the relation between the ratio β/ϕ and the surplus motive force ϕ.

* See, for example, Clerk Maxwell's "Electricity and Magnetism," vol. 2, arts. 437 and 438.

The hypothetical magnet of uniform flux density is shown in section in Fig. 11, and on the principle explained in connection with the leakage sleeve, the sectional area will of course be a maximum at the neutral section, decreasing along each limb towards the ends according to some law to be determined. To simplify matters it will be assumed that the cross section is circular, so that the problem will be reduced to finding the outline of the magnet. We shall assume the steel to be uniformly magnetized in the X direction as a permanent magnet, so that any elementary coaxial cylinder dy will constitute a hollow tube of flux in

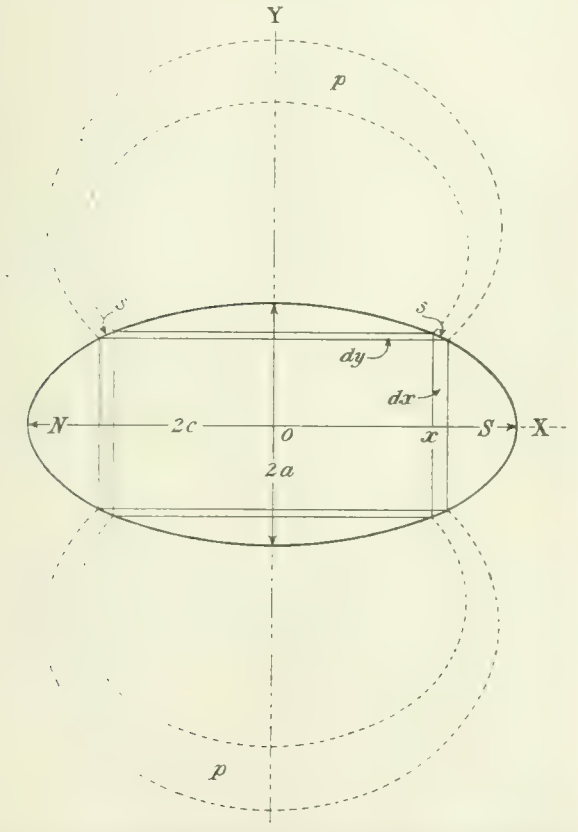


FIG. 11.—Ideal bar magnet of uniform flux density (ellipsoid of circular section).

which the density will be β and the surplus force ϕ. The elementary cylinder ends at two corresponding zones dx and dx' at a distance x on each side of the neutral section, so that the length of the cylinder is $2x$ and the total surplus force available at its ends will be $2\phi x$, that being the terminal potential difference V_x of the elementary magnetic circuit. The sectional area of the cylinder is $2\pi y\,dy$, and hence the flux dB in the elementary circuit will be $\beta . 2\pi y\,dy$. The circuit is completed by the air path shown in section at pp and forming a hollow shell, as it were, symmetrical about the X axis; the air path beginning and ending at the zonal surfaces ss. The relations between the various quantities in the elementary circuit may first be noticed. Denoting the conductance of the air path by k_a we shall have

$$k_a = d\mathrm{B}/V_x = \beta . 2\pi y\,dy/2\phi x,$$

which gives the ratio equation:

$$\frac{\beta}{\phi} = \frac{2x}{2\pi y\,dy} k_a = \frac{\text{conductance of air path}}{\text{conductance of path in steel}}$$

Again, the energy equation is $d\mathrm{B}.V_x = \beta\phi . 2x . 2\pi y\,dy$, or in words, element of energy $= \beta\phi \times$ element of volume of magnet, so that on integration over the whole volume we shall obtain:

$$\text{Total external energy} = \beta\phi \times \text{volume of magnet}$$

a relation which is true of any magnet, or any portion of a magnet, in which the flux density is uniform.

To obtain the differential equation for the outline of the magnet the conductance of the air path pp must be expressed as a differential. We shall therefore put $k_a = q\,dx$, the quantity q, which may be called the "conductance factor," is defined as the leakage or air-path conductance, per cm. of zone-width; it being understood that width of zone is measured in a direction parallel with the X axis. Since

$$k_a = \beta 2\pi y\,dy/2\phi x$$

when $q\,dx$ is substituted for k_a the differential equation becomes:

$$\beta\pi . 2y\,dy = -\phi q . 2x\,dx$$

the negative sign arising from the fact that y necessarily decreases with increasing x. If q is assumed to be constant the integral is obviously:

$$\beta\pi y^2 = \text{a constant} - \phi q x^2$$

which is the equation to an ellipse.

When $x = 0$, $y = a$, which is the radius of the magnet at the neutral section. Hence the integration constant is $\beta\pi a^2$, and after rearrangement the equation for the outline of the magnet becomes:

$$y^2 = \frac{\phi q}{\beta\pi}\left(\frac{\beta\pi a^2}{\phi q} - x^2\right)$$

This is of the form:

$$y^2 = \frac{a^2}{c^2}(c^2 - x^2),$$

which is the equation to the ellipse referred to the centre as origin, $2c$ and $2a$ being the major and minor axes respectively. Hence, to fulfil the conditions of uniform density and therefore uniform surplus force, the outline of the magnet must be an ellipse in which $c^2 = \beta\pi a^2/\phi q$, from which, on transposing, we obtain the ratio equation:

$$\frac{\beta}{\phi} = \frac{c}{\pi a^2} . qc \quad . \quad . \quad . \quad . \quad . \quad (23)$$

$c/\pi a^2$ being the ratio of a length in the steel to the area at the neutral section and qc being the total conductance of the external paths from one magnet

limb to the other. It should be noticed that there is no central core delivering a useful terminal flux at the ends of the magnet, and the ellipsoid is therefore the limiting form assumed by an ideal bar magnet when the area of the central core is zero. In short, it may be regarded as a leakage sleeve which contains no core, the whole of the flux traversing an ellipsoid magnet being tantamount to so much leakage.

(25) The Ellipsoid Magnet as a Single Magnetic Circuit.

Inspection of Fig. 11 shows that an ellipsoid magnet consists of a number of elementary cylinders of steel, each in series with one of an equal number of elementary leakage paths in the form of hollow shells packed one inside the other; the whole system forming what was referred to in the introduction as a bundle of magnetic circuits. Every magnet, no matter what its shape, constitutes a similar, but, in general, a more complicated bundle of circuits; and the energy and ratio equations which we have shown to be true for the core of an ideal magnet are applicable to each elementary circuit in the bundle. But when the flux density in the steel is not uniform, it becomes necessary to ascertain the potential difference which will be available for the inert reluctance of any elementary air path in the bundle, by some process of integration of the surplus force along that part of the elementary circuit which is occupied by steel; and whatever method of integration may be resorted to, the task of forecasting the available energy of the magnet cannot fail to become somewhat laborious.

The matter would be much simplified if it were always possible to treat a magnet as a single magnetic circuit. This may be done in many cases by substituting for the actual magnet an equivalent but imaginary one which would deliver the same flux at the same potential difference. The nature of the substitution to be made will be readily seen in the case of the ellipsoid magnet. Transposing equation (23) so as to give the total flux traversing the neutral section in terms of the other quantities, we shall have:

$$\beta \pi a^2 \mathrm{B} = \phi c \,.\, q c = \tfrac{1}{2}\, 2\phi c \,.\, q c \quad . \quad . \quad (24)$$

but $2\phi c$ is the total surplus motive force which appears as a potential difference V between the ends of the ellipsoid. Again qc is the total air path conductance from one limb of the magnet to the other, a quantity which may be denoted by k_c. Hence, the equation for the total flux traversing the magnet may be written $\mathrm{B} = \tfrac{1}{2}\mathrm{V}k_c$ which is arithmetically (but by no means physically) the same thing as $\mathrm{B} = \mathrm{V}\tfrac{1}{2}k_c$. So far as the flux B is concerned, this transposition is equivalent to saying that for the real conductance k_c on which a mean potential difference $\tfrac{1}{2}$ V is maintained, we may substitute a fictitious conductance of half the amount and imagine it to be connected (as though it could be treated like an electric conductor) to the ends of the magnet, where it would be acted on by the whole potential difference V created by the total surplus motive force $2\phi c$. In doing this, we shall be tacitly replacing the ellipsoid by a steel cylinder of radius a and length $2c$ connected at its ends to an inert conductance $\tfrac{1}{2}k_c$, so that the imaginary cylinder will be traversed from end to end by the flux B; no leakage taking place from the cylindrical surface.

The substitution by which the real magnet is replaced by an imaginary one with leakage paths concentrated into a single conductance connected to the ends of the magnet limbs, is an arithmetical device of the greatest utility in dealing with ordinary magnets, because it enables the ratio equation (20) to be applied in any case in which only a rough forecast of terminal flux and potential difference is required.

Having made this substitution the ratio equation becomes:

$$\frac{\beta}{\phi} = \frac{\mathrm{L}}{\mathrm{A}}(k_u + k_p + \tfrac{1}{2}k_c) \quad . \quad . \quad . \quad . \quad (25)$$

where k_c is the estimated leakage conductance from one limb of the magnet to the other. It should be noticed, however, that in ordinary magnets the numerical coefficient is not exactly $\tfrac{1}{2}$ as it is for the ellipsoid, and to be strictly correct the equivalent fictitious conductance connected at the ends of a magnet should be defined as being αk_c, where α is some fraction the precise value of which depends on the shape of the magnet.

In the case of the ellipsoid no substitution of an equivalent conductance is needed, but the artifice has been introduced here because it follows at once from the equation for the total flux in an ellipsoid magnet.

(26) Leakage Conductance between Magnet Limbs.

Predetermination depends, among other things, on our ability to make reasonably close estimates of the conductance of leakage paths from one limb of a magnet to the other, and hence what we have called the conductance factor, the conductance per cm. of zone width at any pair of corresponding zones on the magnet limb, is a quantity of great practical importance. In general the value of q varies, from a minimum for zones in the neighbourhood of the neutral section to a maximum for the zones at the ends of the magnet. In the majority of cases which occur in practice q does not vary widely between the neutral section and points about half-way along the magnet limbs, the greater part of the whole change in magnitude occurring in the region between the half-way points and the ends of the magnet. In practice, therefore, q may be treated as being constant over the first half length of the limbs, and since the potential difference between the limbs within that region is comparatively small, the corresponding leakage flux will always be a small proportion of the whole. Hence, for the first half length of any magnet, a roughly-estimated value for q may be used without introducing a noticeable error in predetermination.

In any ordinary magnet the conditions as regards leakage paths in the space round about the neutral section, do not differ much from those round about an ellipsoid, or any other bar magnet, and it may be safely assumed that for a region extending over some-

thing like half the length of the magnet the conductance factor will not be very different from the value of q for an ellipsoid in which the proportion between length and diameter is the same. It is therefore convenient in practice to have at hand the means of determining q for any ellipsoid in terms of the dimension ratio c/a.

(27) Value of Conductance Factor q in Terms of the Dimension Ratio of an Ellipsoid.

Returning to Fig. 11, it is clear that the value of q depends on the shape of the surfaces forming the boundaries of the hollow shell $p\,p$ which constitutes an elementary air path of conductance $q\,dx$. Now the forms assumed by these surfaces are determined by the stresses which we assume to exist in the magnetic medium as the result of the magnetomotive forces of the current rings. Hence, to determine q on a geometrical basis, it would be necessary at the outset to deduce the forms of the boundary surfaces from the assumed stresses; a formidable problem which awaits solution. In the meantime, however, we can find q indirectly by making use of the older theory which ignores the medium.

Taking any one of the bundle of magnetic circuits formed by an ellipsoid magnet, let R denote the reluctance of the elementary cylinder of steel, and r that of the air path in series with it, so that $R = 2x/2\pi y\,dy$ and $r = 1/q\,dx$. The ratio R/r will therefore be $q.2x\,dx/\pi.2y\,dy$, and since from the equation to the ellipse $2y\,dy/2x\,dx = a^2/c^2$ we shall have:

$$q = \frac{R}{r}\cdot\frac{\pi}{c^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (26)$$

Denoting the motive force of the steel by F we have (equation 7) $F = \beta + \phi$, since β is numerically equal to the motive force which is expended in the steel. But by equation (22) $\beta/\phi = R/r$, or $\phi = \beta r/R$, and hence:

$$F = \beta + \beta\frac{r}{R} = \beta\frac{R + r}{R}$$

so that

$$\beta = F\frac{R}{R + r} = F\frac{R + r - r}{R + r} = F\left(1 - \frac{r}{R + r}\right)$$

Hence

$$\beta = F - F\frac{r}{R + r}$$

Denoting the equivalent current in the oriented steel by I, we have $F = 4\pi I$ and hence:

$$\beta = 4\pi I - \frac{4\pi r}{R + r} I \quad . \quad . \quad . \quad . \quad (27)\ *$$

On the basis of textbook theory, in which Faraday's induction and Poisson's magnetism are rather incongruously mingled, the induction in the steel is equal to $4\pi J + h$ where h is the net "magnetic force" in the steel, and J is the intensity of magnetization. But $h = H - N J$ where N J is a supposititious magnetic force which would be created inside a piece of magnetized steel by the action of positive and negative magnetic matter located at its ends. Hence the induction is equal to $4\pi J + H - N J$, and when the steel is in the permanently magnetized state and the extraneous force H is zero, the induction becomes:

$$\beta = 4\pi J - N J \quad . \quad . \quad . \quad . \quad . \quad (28)\ *$$

Now as we have seen (section 19) intensity of magnetization and equivalent current are merely two names for the same quantity, the aggregate effective current in the mass of oriented current rings, and hence comparing (28) with (27) we find:

$$\frac{4\pi r}{R + r} = N, \quad \text{or} \quad \frac{r}{R + r} = \frac{N}{4\pi} \quad . \quad . \quad . \quad (29)$$

that is to say, $N/4\pi$ is the proportion which the inert reluctance external to the magnet bears to the whole reluctance of the magnetic circuit.

In an ellipsoid of circular cross section N is a constant depending solely on the dimension ratio c/a and putting $c/a = m$,

$$\frac{N}{4\pi} = \frac{1}{m^2 - 1}\left\{\frac{m}{\sqrt{(m^2 - 1)}}\log_e\left[m - \sqrt{m^2 - 1}\right] - 1\right\}.\dagger$$

Inverting equation (29) we obtain:

$$\frac{R - r}{r} = \frac{R}{r} + 1 = \frac{4\pi}{N}, \quad \text{or} \quad \frac{R}{r} = \frac{4\pi}{N} - 1, \quad . \quad (30)$$

and substituting this equivalent for R/r in equation (26) we have finally:

$$q = \frac{\pi a^2}{c^2}\left(\frac{4\pi}{N} - 1\right) \quad . \quad . \quad . \quad . \quad . \quad (31)$$

and since N depends only on the dimension ratio c/a the value of q also depends solely on the dimension ratio. A table of values for q in terms of c/a is given in the Appendix, and will be found useful in estimating leakage conductance for ordinary magnets.

(28) Predetermination of Ellipsoid Magnets.

From the ratio equation (22) and equation (30) the induction, total flux, and surplus force in an ellipsoid magnet of given dimensions may be predetermined with accuracy by means of the equation:

$$\frac{\beta}{\phi} = \frac{R}{r} = \frac{4\pi}{N} - 1 \quad . \quad . \quad . \quad . \quad . \quad (32)$$

the separate values of β and ϕ being ascertained from curves derived from the demagnetization curve of the steel, like those shown in Fig. 9 and Fig. 10.

The induction and surplus force having been predicted from the dimension ratio of the ellipsoid and

* Equations like (27) and (28) are only statements of arithmetical fact. It is physically impossible for an induction in the negative direction to coexist in one and the same place with an induction in the positive direction; although, as a matter of arithmetical convenience, we may pretend they do so and subtract the negative from the positive induction. In equation (28) the terms are regarded as mechanical forces; the forces which would be exerted on the supposititious unit pole if it were there. The quantity N J being in the opposite direction to the magnetization, is called the demagnetizing force. Its existence as a physical reality depends on the existence of the magnetic attractive matter which alone can give rise to it, but magnetic matter which was never more than a highly ingenious mathematical artifice, has long been consigned to limbo, and hence at the present day the demagnetizing force only survives as a mathematical ghost.

† Clerk Maxwell, loc. cit., vol. 2, art. 438.

the demagnetization curve of the steel, it may easily be shown that the magnetic moment of an ellipsoid magnet is :

$$M = \tfrac{1}{3} a^2 c (\beta + \phi) \quad . \quad . \quad . \quad . \quad . \quad (33)$$

Again, the external energy maintained by an ellipsoid magnet can be expressed in terms of flux and potential difference when β and ϕ are known. For the energy is $\beta\phi \times$ volume of magnet, and since the volume of an ellipsoid of circular cross section is $\frac{4}{3}\pi a^2 c$ the external energy will be $\beta\phi \frac{1}{3} \pi a^2 c = \beta \pi a^2 . \frac{2}{3} 2\phi c$. But $\beta \pi a^2$ is the total flux in the magnet, and $2\phi c$ is the potential difference between its ends. Hence, putting V_t for the end potential difference, we have :

$$\text{External energy of ellipsoid magnet} = \tfrac{2}{3} B V_t \quad . \quad . \quad (34)$$

(29) Permanent Magnet Diagrams.

In practice it is often useful to draw graphs showing the magnitude of the significant magnetic quantities and their variation along the length of a magnet ; or along one limb, since there is usually magnetic symmetry about the neutral section. A diagram of this kind is given in Fig. 12 for the simple case of an ellipsoid magnet. Flux density and surplus force being constant in this case, the graphs of those quantities are straight lines parallel with the base line. Denoting the flux at the neutral section by B, the flux traversing any cross section at a distance x from the neutral section will be :

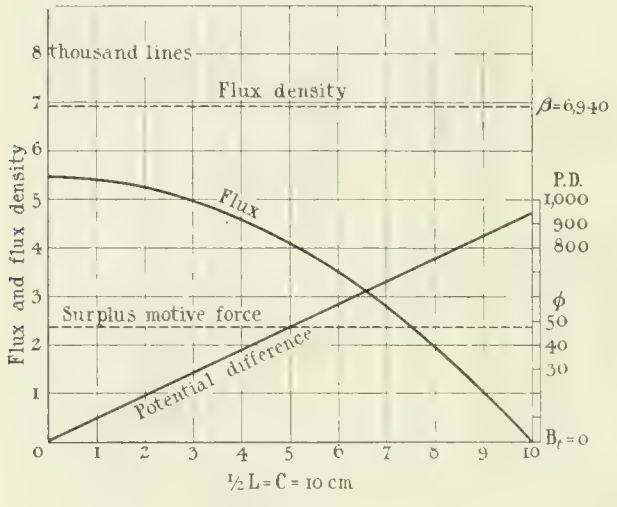


Fig. 12.—Magnet diagram for an ellipsoid magnet of the same steel as test-piece B 32, J 1 (Figs. 8, 9 and 10), length of magnet 20 cm., diameter at neutral section 1 cm., $c/a = 20$.

$$B_x = \beta \pi y^2 = \beta \pi a^2 (1 - x^2/c^2) = B(1 - x^2/c^2)$$

from which it is evident that the graph representing flux variation along the magnet is a parabola of which the axis is O Y with the vertex at B. The surplus force being constant, the graph representing the accumulation of surplus force along the magnet, which appears as a potential difference, is a straight line inclined at an angle to the base line. In similar diagrams relating to ordinary magnets in which the flux density is not uniform, the graphs for flux density, surplus force and potential difference, naturally show more or less curvature, the potential difference V_x at any section being $\int_0^x \phi\, dx$, an integral which can only be determined by an arithmetical step-by-step process.

(30) The Design of Economic Magnets of Uniform Sectional Area. (Ordinary Magnets.)

Present-day practice gives the magnet uniform sectional area because magnet steel is supplied in the form of rolled bars, and on passing from the ideal magnet of uniform flux density, to the ordinary magnet of everyday use, we are faced by the difficult problems which arise from variation of flux density in the steel. For economy in an ideal magnet it is only necessary to choose the particular flux density which gives the product $\beta\phi$ its maximum value. But in the everyday magnet, with a flux density varying from a maximum at the neutral section to a minimum at the ends, there is a corresponding variation in $\beta\phi$. Now, although the magnet may be (and should be) so proportioned that $\beta\phi$ attains its greatest possible value somewhere in each limb, it is obvious from inspection of the energy curve, Fig. 8, that the *average* value of $\beta\phi$ for any range of variation in flux density, must fall short of the maximum product. Some sacrifice in economy of steel is therefore unavoidable in an ordinary present-day magnet, and the problem of the designer is to find the length and sectional area of steel which will result in the highest *average* value of the product $\beta\phi$, in the whole magnet, which is consistent with the unfavourable condition imposed by uniform sectional area of steel. To put the matter in another way, with variation in flux density, economy of steel cannot be based simply on the ideal economic density. We must be content to aim at an economic *region* extending above and below the ideal density ; a range of variation in flux density which will give to the average product $\beta\phi$ the highest practicable value under the restrictive condition of uniform section of steel. Accepting this restriction as inevitable (at all events at the present time) a magnet designed to secure the highest practicable mean value for $\beta\phi$ may be regarded as an economic magnet, although it cannot show an economy of steel equal to that of the ideal magnet of uniform flux density. Needless to say, the problem of finding the most favourable region of density variation cannot be solved with precision, but, representing the maximum value of $\beta\phi$ by $\beta_e\phi_e$, it is found in practice that when a magnet is so designed that the *average* surplus force in the steel is not very different from ϕ_e, the range of variation in flux density coincides sufficiently well with the most favourable region for economy of steel.

Although design and predetermination are distinct problems, they must always go together in determining the dimensions of a magnet. Design begins with an estimate of the approximate length L and sectional area A of an economic magnet to fulfil some given

energy requirement BV. With the figures so obtained, the next step is to make a forecast of what a magnet of that size will do, and then on the basis of the forecast, to make any final corrections in the size of the magnet which may be necessary. Again denoting the maximum energy product by $\beta_e\phi_e$ the length of the magnet is found at once by putting $L = V/\phi_e$, and it is seldom that any material correction of the length ascertained in this way will be required. Finding the sectional area is not such an easy matter, and in the absence of previous experience of magnets of similar shape, it can only be done by a series of approximations. Adopting the arithmetical artifice of an equivalent fictitious conductance, explained in section 25, we shall suppose the whole of the leakage flux passing from limb to limb to be transferred to the ends of the magnet. Denoting the leakage flux by b we shall probably err on the safe side if we put $b = \frac{1}{2}Vk_c$, where k_c stands for the conductance of the leakage paths deduced from the final dimensions of the magnet, L and A. The total flux in the magnet will be $B + b$, and if we aim at an average density equal to β_e we must find an area A and the corresponding leakage flux b which satisfies the equation $A = (B+b)/\beta_e$. One method of approximation is to begin with the provisional value $A_0 = B/\beta_e$, and from the leakage conductance based on A_0 and L to find a provisional value b_1 for the leakage flux, from the relation $b = \frac{1}{2}Vk_c$. The total flux will now be $B + b_1$ which gives an increased value to the area, namely $A_1 = (B + b_1)/\beta_e$, and from A_1 and L the leakage conductance is determined afresh, making the leakage flux b_2, from which we shall have $A_2 = (B + b_2)/\beta_e$. Proceeding in this way, the values for sectional area and leakage flux rapidly approach corresponding amounts, and after a few approximations final values may be assigned to A and b so as to make $A = (B + b)/\beta_e$. The process is greatly simplified if, after finding b_1, the next step is made by doubling the provisional value of the leakage flux and so obtaining $A_2 = (B + 2b)/\beta_e$. Here, in practically every case, A_2 will be greater than the required area, and as A_1 is less than the proper value, inspection of the figures usually enables the correct value A to be ascertained at once, without anything more elaborate than a rule-of-three sum. In calculations of this kind there is no royal road, and with a little practice and the exercise of mother wit, alternative ways of making a rapid approximation naturally suggest themselves. The problem is closely analogous to that of finding the sectional area of the core of a dynamo field-magnet, but a much greater precision is required in the case of the permanent magnet, where in determining area and length we are once for all settling the magnetomotive force, the inherent "ampere-turns" for excitation, and not merely providing a path for the magnetic flux.

(31) Predetermination of Ordinary Magnets, using the Ratio Equation.

Assuming the economic length and sectional area have been ascertained the energy output of the magnet may be predetermined from the ratio equation, or when an accurate and more detailed forecast is required the more laborious method of step-by-step integration may be resorted to. Taking first the approximate method of the ratio equation, the problem is to find the terminal potential difference that the magnet will maintain when used with the apparatus for which it is intended. The estimated data derived from the proposed magnet itself, are the length L and sectional area A, and the conductance k_c of the leakage path from one limb to the other; those pertaining to the apparatus being the united conductance k_p of all leakage paths between what we may call the magnetic terminals of the apparatus and the conductance k_u of the path traversed by the useful flux. Assuming the leakage conductance of the magnet to be equivalent to a fictitious conductance αk_c connected at the ends of the magnet, the ratio equation is (section 25):

$$\frac{\beta}{\phi} = \frac{L}{A}(k_u - k_p - \alpha k_c)$$

Having determined the ratio β/ϕ in this way, the average surplus force is ascertained by reference either to the demagnetization curve; or, more conveniently, to a derived curve like that shown in Fig. 10 which gives ϕ in terms of β/ϕ at a glance. Denoting the value of the average surplus force, predetermined in this way by ϕ_a, the corresponding terminal potential difference will be:

$$V = \phi_a L \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (35)$$

and the useful flux will therefore be:

$$\Phi_u = Vk_u = \phi_a L k_u \quad . \quad . \quad . \quad . \quad . \quad (36)$$

The terminal flux delivered to the apparatus will be $V(k_u + k_p)$, and hence the predetermined energy delivered by the magnet will be $V^2(k_u + k_p)$. It should be observed that although the first step in design was to make $L = V/\phi_e$, it by no means follows that for a magnet so designed, the predetermined value of the average surplus force ϕ_a will turn out to be exactly equal to the ideal economic value, and hence, after making a forecast by means of the ratio equation, it may be necessary to modify the length and sectional area in order to obtain predetermined values for terminal potential difference and flux in sufficiently close agreement with the two factors of the required energy.

The accuracy of a forecast derived from the ratio equation depends, among other things, on the value assigned to the coefficient α. That this coefficient is connected in some way with the shape of the magnet is evident, but no simple rule for predicting its value in any particular case has so far suggested itself. As we have seen, in an ellipsoid magnet α is exactly $\frac{1}{3}$, but experience derived from a considerable number of examples shows that in ordinary magnets α may have any value between about $\frac{1}{3}$ and about $\frac{1}{2}$, and if the latter fraction is assumed to be the upper limit, we shall err on the safe side if we adopt it in making a forecast. In a well-designed magnet leakage from limb to limb does not generally form so large a proportion of the total flux as to call for great precision

in the estimated conductance ak_c of the equivalent leakage path.

By assuming that what is exactly and demonstrably true for the ellipsoid is approximately true for any ordinary magnet—that is to say, that an ordinary magnet, in common with an ellipsoid, behaves in some respects like a single magnetic circuit—we convert the ratio equation into a useful tool for the designer. But the arithmetical device which enables the equation to be applied in this way, the substitution of a leakage conductance concentrated at the ends of the magnet for the real distributed leakage conductance, is tantamount to substituting for the real magnet an imaginary one which is traversed from end to end by a flux equal to $V(k_u + k_p + ak_c)$. Hence, the utility of the equation is confined to the estimation of terminal potential difference and terminal flux. It does not afford any information relating to the distribution of flux and variation of flux density in the steel—matters on which economy and magnetic efficiency largely depend.

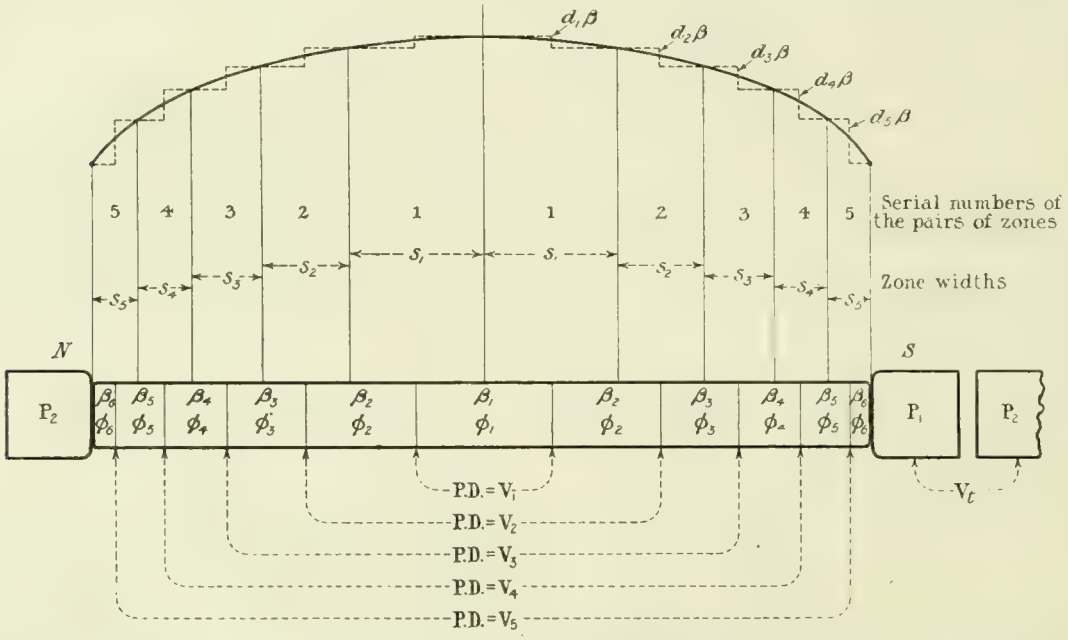


FIG. 13.—Diagram illustrating the method of step-by-step integration, the length of the magnet being divided into regions of uniform flux density, and into pairs of leakage zones. The diagram corresponds with Table 2.

(32) PREDETERMINATION BY STEP-BY-STEP INTEGRATION.

For a comprehensive predetermination, a detailed estimate of the magnetic flux and energy maintained by a permanent magnet, it is necessary to bring the variation in flux density and surplus force in the steel within the range of arithmetic. For this purpose we may suppose the magnet to be sub-divided into a number of lengths or regions within which β and ϕ may be treated as constant quantities, their values being supposed to change *per saltum* in passing from one region to the next. On this supposition, leakage from the magnet limb will take place solely at the junctions between adjacent regions, each junction being treated as the centre of a leakage zone.

The method of sub-division into regions of uniform flux density is given in Fig. 13, which shows a typical density variation curve from one end of a magnet to the other, the sectional area of the magnet being uniform. The magnet, which we may suppose to be of the bent or horse-shoe form, is shown as a development, so that the magnetic axis appears as a straight line.

The space to be magnetized consists of an air gap between two pole-pieces P_1 P_2. The magnet is divided into a number of pairs of regions, symmetrically disposed, on either side of a central region, and it might naturally be supposed that accuracy of predetermination would depend mainly on the extent to which sub-division was carried. This, however, is not the case because, in practice, accuracy is limited by sources of error which would not be removed by the most minute sub-division. Two or three pairs of regions on either side of the central region are in nearly all cases sufficient to predetermine the terminal flux and potential difference, but when it is intended to obtain data for graphs showing variation in flux density and other quantities along the magnet limbs, then half a dozen pairs of regions would not be excessive. As a general rule, magnets without pole-pieces require a finer sub-division than magnets which are to be used with pole-pieces, the range of variation in flux density being much greater in the absence of pole-pieces, or magnet ends which are the equivalent of pole-pieces.

By way of example, the magnet in Fig. 13 is divided into five pairs of regions on either side of the central

region. The dotted line following the flux density curve indicates the hypothetical mode of variation by steps which would result from division into regions of uniform density, and in view of the shape of actual density variation curves a small advantage may sometimes be gained in accuracy by graduating the length of the regions more or less as indicated in the diagram, so as to avoid excessive inequality in the height of the steps. The advantage, such as it is, involves a sacrifice of the arithmetical simplicity of regions of uniform length, and is seldom worth while.

Since the junctions between the regions are the centres of leakage zones, there will be five pairs of leakage zones arranged on either side of the neutral section. The conductance of the leakage path between any pair of zones will be equal to the estimated value of the conductance factor q for the particular zones, multiplied by the zone width; the conductance being supposed to be connected at the centres of the zones, so that leakage is concentrated and takes place at the junction between regions of uniform density.

The arithmetical process of summation or integration

TABLE 2.

Illustrating in Symbols the Arithmetical Process of Step-by-step Integration along a Magnet (see Fig. 13).

Serial Number of Zone	For Increments of Potential Difference: Flux Density	Surplus Motive Force	Length of Regions in which φ is uniform	Potential Difference V, at Centre of Zones	For Decrements of Flux Density: $V \cdot \frac{qs}{A} \cdot \delta\beta$	$\frac{qs}{A}$	Factor	Zone Width	Energy in Leakage Paths	Serial Number of Zone
				zero						
	β_1	ϕ_1	s_1	$\phi_1 s_1$						
	$-\delta_1\beta$									
1				V_1	$\delta_1\beta$	$\frac{q_1 s_1}{A}$	q_1	s_1	$V_1^2 q_1 s_1$	**1**
	β_2	ϕ_2	$s_1 + s_2$	$\phi_2 (s_1 + s_2)$						
	$-\delta_2\beta$									
2				V_2	$\delta_2\beta$	$\frac{q_2 s_2}{A}$	q_2	s_2	$V_2^2 q_2 s_2$	**2**
	β_3	ϕ_3	$s_2 + s_3$	$+\phi_3 (s_2 + s_3)$						
	$-\delta_3\beta$									
3				$= V_3$	$\delta_3\beta$	$\frac{q_3 s_3}{A}$	q_3	s_3	$V_3^2 q_3 s_3$	**3**
	β_4	ϕ_4	$s_3 + s_4$	$\phi_4 (s_3 + s_4)$						
	$\delta_4\beta$									
4				V_4	$\delta_4\beta$	$\frac{q_4 s_4}{A}$	q_4	s_4	$V_4^2 q_4 s_4$	**4**
	β_5	ϕ_5	$s_4 + s_5$	$-\phi_5 (s_4 + s_5)$						
	$-\delta_5\beta$									
5				$= V_5$	$\delta_5\beta$	$\frac{q_5 s_5}{A}$	q_5	s_5	$V_5^2 q_5 s_5$	**5**
	β_6	ϕ_6	s_5	$-\phi_6 s_5$						
				P.D. $= V'$						
	Terminal flux $-\beta_6 A = B'$				Total energy in leakage from limb to limb $=$				Sum of above terms	

To correspond with the above quantities, the terminal conductance must be equal to the ratio B'/V'.

is set out in Table 2, and begins with the arbitrary choice of an initial flux density β_1 for the central region. Reference to the demagnetization curve of the steel from which the proposed magnet is to be made, gives the corresponding value of the surplus force ϕ_1 which when multiplied by the length of the region, namely $\frac{1}{2} s_1$ on one side of the neutral section plus $\frac{1}{2} s_2$ on the other side, gives the potential difference V_1 between the centres of the first pair of leakage zones. Denoting the sectional area of the magnet by A and the conductance of the first leakage path being $q_1 s_1$, the decrement in flux density at the junctions between the central region and the adjacent regions on either side of it will be $V_1 q_1 s_1/A$. In Fig. 13 and in the table this decrement is denoted by $\delta_1 \beta$.

Next, by subtracting $\delta_1 \beta$ from β_1 the density at the bottom of the first step in each limb is ascertained. Denoting the density so found by β_2, the corresponding surplus force ϕ_2 is ascertained by referring again to the demagnetization curve of the steel, and in that way the next increment in potential difference, namely $\phi_2 (s_1 + s_2)$, is determined. Adding together V_1 and $\phi_2 (s_1 + s_2)$ gives the potential difference V_2 between the centres of the second pair of leakage zones, and the decrement of density at the second step in each limb will be $V_2 q_2 s_2/A$. Denoting the second decrement in density by $\delta_2 \beta$, the flux density at the bottom of the second step will be $\beta_2 - \delta_2 \beta = \beta_3$ and again the corresponding value of the surplus force, namely ϕ_3, is found by reference to the demagnetization curve.

Proceeding in this way, step by step, to the ends of the magnet, a terminal density β_6 is found, which when multiplied by A gives a terminal flux which we shall denote by B′. At the same time the successive additions of the increments of potential difference will have resulted in a terminal potential difference which we shall denote by V′.

In settling the energy requirement of the apparatus—pole-pieces and air gap in the present case—we shall have obtained estimated values for the conductance k_u of the space traversed by the useful flux and the total conductance k_p of leakage paths in the apparatus, and it will be convenient to put $k_u + k_p = k_t$, so that k_t is the total estimated conductance between the magnetic terminals of the apparatus. Now it is clear that the flux and potential difference, as delivered by any magnet whatever when applied to the given apparatus, must necessarily bear a ratio to each other equal to the apparatus conductance k_t. But since our integration started with an arbitrary choice for the initial flux density, all we learn from it is that the proposed magnet would deliver a flux B′ at a potential difference V′, if it were applied to some apparatus which had a total conductance equal to B′/V′, and hence B′/V′ could only turn out to be equal to k_t by some unexampled stroke of luck in the choice of an initial density for the starting point. What we have to do, therefore, is to determine the particular value of initial density which after integration will result in a terminal flux B_t and terminal potential difference V_t, the values of which will make B_t/V_t equal to k_t. For this purpose it is necessary to carry out a second and in nearly every case a third integration, similar to that just described but beginning with different initial densities. Assuming the terminal ratio B′/V′ which resulted from the first integration to be greater than k_t, the second integration must start from an initial density less than that chosen for the first. The second integration will result in a terminal ratio which may be denoted by B″/V″ and, again, if B″/V″ should be greater than k_t, the third integration must begin with an initial density less than that chosen for the second; the rule being reversed, of course, if the differences are the other way about. Assuming a third integration has been made, the three integrations starting from three initial densities, which may be denoted by β_1' β_1'' and β_1''', will have resulted in three terminal ratios B′/V′, B″/V″ and B‴/V‴; and assuming these to represent the initial densities and terminal ratios in order of magnitude, it is essential that k_t should come somewhere between B′/V′ and B‴/V‴ in magnitude. It is easy to fulfil this condition by choosing for the first integration an initial density not very far below the maximum remanent density of the steel. For by so doing it will be found that B′/V′ turns out to be greater than k_t in almost every case that is likely to occur in practice, and by noting the difference between B′/V′ and k_t it is an easy matter to make an appropriate choice for the initial density with which to begin the second integration. The author has found it good practice in choosing the initial density for a first integration to take some convenient whole number about 1,000 lines below the maximum remanent density. In exceptional cases a suitable figure for initial density can be found by means of the ratio equation which gives an approximate value for the ratio β/ϕ at some cross section in the magnet limbs. The value of β ascertained in this way will serve quite well as the starting point for integration, although in this case B′/V′ is likely to be less than k_t.

Having obtained three terminal ratios B′/V′, B″/V″ and B‴/V‴, covering a range of values which includes that of the terminal conductance k_t, the particular value of initial density which, after integration, would result in a terminal ratio $B_t/V_t = k_t$ is ascertained by drawing a curve connecting initial density with terminal ratio, or what is numerically the same thing, terminal or "apparatus" conductance. For this purpose the connected quantities β_1', with B′/V′, β_1'' with B″/V″ and β_1''' with B‴/V‴ are plotted as co-ordinates and a curved line drawn freehand through the plotted points. The required initial density is then found by noting the point at which the line passes through the ordinate k_t.

In the same way the terminal potential difference is found by means of a curve plotting the three values V′, V″ and V‴ with the corresponding terminal ratios B′/V′, B″/V″ and B‴/V‴. Again, the terminal flux may be found in a similar way by means of a curve, in this case plotting B′, B″ and B‴ with the corresponding terminal ratios; but it should be observed that when one of the energy factors has been ascertained by means of a graph, the simpler plan is to find the other factor from the relation $B_t = k_t V_t$.

From these three integrations the following data

will have been obtained relating to the predicted performance of the magnet when used with the given apparatus. The terminal flux B_t; the terminal potential difference V_t; the flux density β_1 in the central region, which for practical purposes may be treated as the density at the neutral section, and therefore the maximum density in the steel; and the flux density β_t at the ends of the magnet, which is, of course, B_t/A. To ascertain how nearly the magnet will fulfil the given requirement we have only to compare B_t with B, and V_t with V, a comparison which points the way to any modification in length or sectional area which may be thought necessary. As regards economy of steel, it should be noticed that the mean flux density between the extreme values, namely $\frac{1}{2}(\beta_1+\beta_t)$, ought not to differ widely from the economic density β_e nor should the average surplus force V_t/L differ much from the economic value ϕ_e. If these quantities compare reasonably well together, there will be some approach to an economical use of the volume of steel, LA, contained in the magnet, but it is not possible to reach a more precise conclusion from the data we have derived from three integrations.

For complete information relating to the distribution of flux, the amount of energy utilized and the amount wasted, it is necessary to carry out a fourth integration in about half a dozen steps, the starting point being the predicted value of the initial density which has been ascertained from the three integrations by the means described above. Apart from small arithmetical discrepancies which may creep in, the final integration should, of course, result in a terminal flux B_t and terminal potential difference V_t, and hence the terminal ratio B_t/V_t will have the required value k_t. Incidentally, the precision of the final agreement with the given terminal conductance k_t affords a check on the figures derived from the preliminary three integrations, and it may be remarked that in practice there is usually a very close agreement.

The intermediate figures for flux density, surplus force and potential difference, which occur in the course of the fourth integration are, of course, the values required for plotting the curves in a diagram showing the variation of these quantities between the neutral section and the ends of the proposed magnet. It will be seen by reference to the last column in Table 2 that the intermediate figures also provide the necessary data for estimating the magnetic energy which the magnet will maintain in the leakage paths from one limb to the other; the sum of the terms which represent the energy in leakage paths between successive pairs of zones, being the total energy wasted in leakage from limb to limb. Adding this to the energy B_tV_t delivered at the ends of the magnet—the terminal energy—we obtain the estimated figure for the total magnetic energy maintained by the magnet in space external to the magnet itself. By comparing the figure so obtained with the maximum external energy which the volume of steel contained in the magnet is capable of maintaining, namely $\beta_e\phi_e \times$ (volume of magnet), it will be seen how far the proposed magnet falls short of an ideal magnet of the same volume, as regards economy of steel. In short, a measure is obtained for both the overall energy efficiency of the magnet, and the shortcomings of the designer and his design.

Predetermination by step-by-step integration presents no serious difficulty at any stage. The preliminary work of estimating the conductance of the various leakage paths should be done with care, and some exercise of judgment is called for in choosing appropriate methods for determining the value of the conductance factor q for the different pairs of zones along the limbs of the magnet. But the actual work of integration, although somewhat laborious, involves nothing more than the reading of ordinates on the demagnetization curve and the performance of a number of simple sums in addition, subtraction and multiplication; the latter being done on a slide rule of course.

(33) Comparison between Predetermined and Observed Magnetic Quantities.

How far the methods of predetermination described in the foregoing sections may be trusted in practice

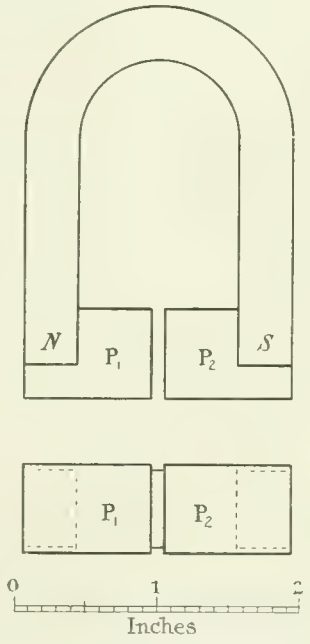


Fig. 14.—Example of predetermination: a small bent magnet with pole-pieces and air-gap.

can only be demonstrated by comparing the predetermined quantities with corresponding values obtained experimentally by testing the completed apparatus. In most cases structural parts of the apparatus prevent a detailed verification by means of search coil and ballistic galvanometer, and under the conditions in which magnets are used in practice it is seldom possible to do more than measure the field or the flux actually obtained; the measurement often being of an indirect character.

The author has made use of the integration method for many years past, but the difficulties met with in applying it in practice have only gradually been sur-

mounted and in early days discrepancies of 10 per cent or more were the rule rather than the exception. Within recent years, however, the use of more trustworthy demagnetization curves and the elimination of various sources of error have brought the outstanding discrepancies within reasonable limits. Predetermina-

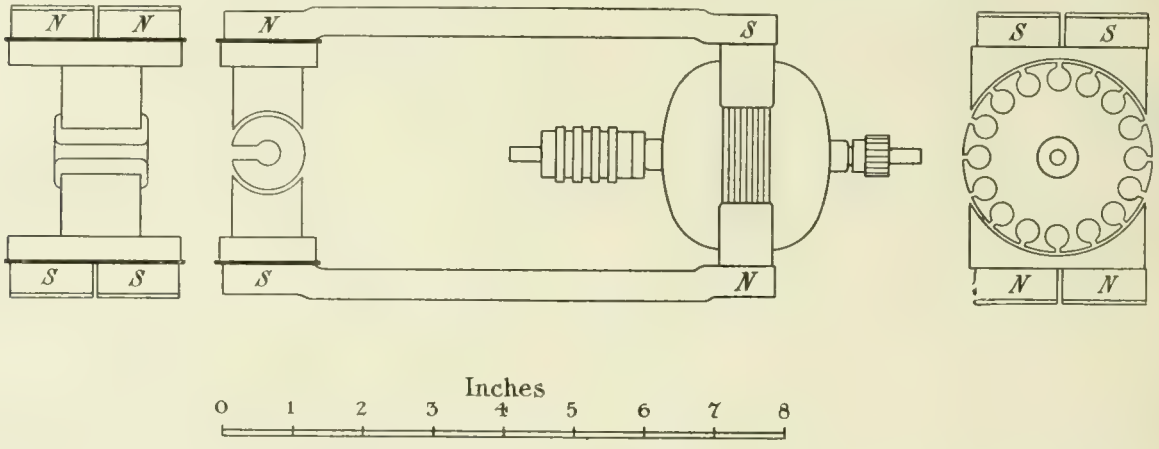


FIG. 15.—Example of predetermination: the magnetic system of the Megger Testing Set.

tions made during the past four or five years have in nearly all cases turned out to be in agreement with realized values within limits of error round about 3 per cent, and the larger discrepancies which still occasionally occur can always be traced to some accidental difference in magnetic quality between the magnet and the test-piece from which the demagnetization curve was obtained. These differences arise in more than one way. The preparation and hardening of test-pieces under laboratory conditions has now reached a precision and uniformity which are not attained, perhaps not attainable, in making magnets under workshop conditions, and occasionally a considerable difference arises from this cause. But the larger discrepancies are more often due to an actual want of uniformity in the steel itself, a trouble which is of far too frequent occurrence. It may be anticipated that discrepancies attributable to these causes will tend to diminish as rule-of-thumb manufacture gives place to systematic methods, but they are unlikely to be removed altogether.

Three typical examples of verification after predetermination are given in Table 3, the magnets themselves being shown in Figs. 14, 15 and 16.

In each of these examples, the magnetic conductance of leakage paths extending more or less radially outwards from the pole-pieces, was estimated by the spherical pole formula given in the Appendix. The conductance of the short leakage paths passing more directly between the pole-pieces, and that of the path traversed by the useful flux, were estimated by methods which have been common practice since the time of

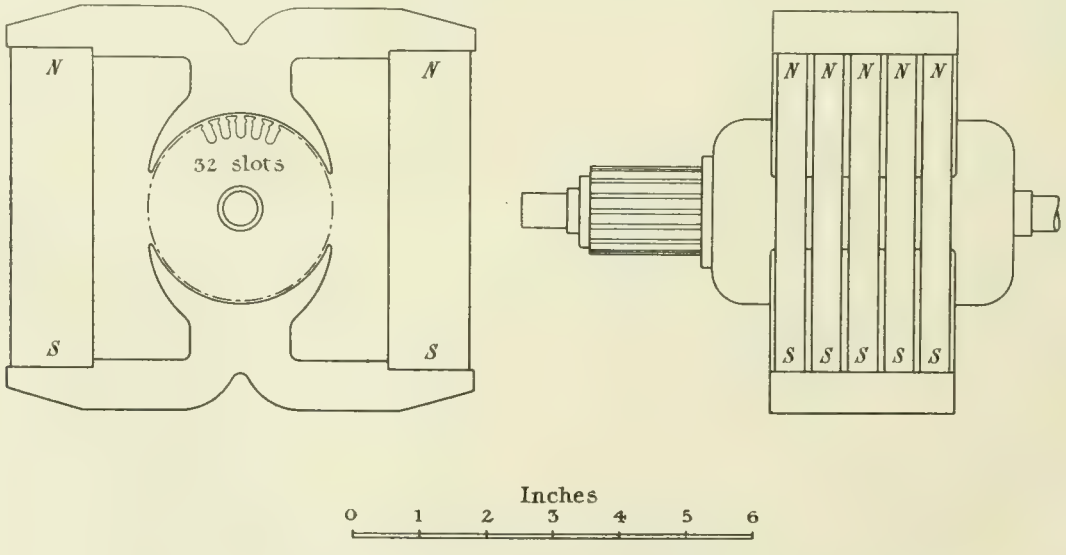


FIG. 16.—Example of predetermination: the magnetic system of a magneto generator.

Hopkinson and need not be described here. It will, however, be useful to indicate in each case the methods chosen for estimating the conductance of the leakage paths from one limb of the magnet to the other. For the little bent magnet shown in Fig. 14, the conductance factor q was assumed to be the same as that of an ellipsoid of ratio c/a equal to the ratio of the magnet, namely length divided by virtual diameter. The value so obtained was applied to the region on either side of the neutral section which is included in the bend. For the parallel parts of the magnet limbs, q was estimated by means of the formula for parallel cylinders which is given in the Appendix. Bent magnets of this type form a very numerous class and the same procedure is applicable to them all. The next example, Fig. 15, is peculiar in having one magnet system to magnetize two different pieces of apparatus, a magneto generator and a moving-coil ohmmeter. The conductance factor for the leakage paths from one magnet limb to the other was first estimated in the ordinary way by the formula for parallel cylinders; but as the substitution of a cylindrical cross section for the rectangular section of the magnet seemed of doubtful validity in the case of a rectangle differing so widely from a square, a second estimate was made by treating each individual bar of steel as a cylinder and assuming that each pair of cylinders utilized one half of the entire surrounding space. These alternative methods gave $q=2\cdot10$ and $q=2\cdot09$ respectively, and the forecast was based on the first of these figures. It may be noted that a rough estimate made by drawing freehand lines of force between the limbs, a method which unavoidably omits the conductance of the remoter regions of space, gave the value $q=1\cdot83$.

The third example, Fig. 16, is a novel type of magneto generator designed by the author; and being the first machine of its kind it was of special interest to see how closely the estimated performance of the field-magnet system would be realized in practice. The output and speed of the machine being specified, the necessary flux in the armature was estimated to be 196,000 lines, and to maintain that flux it was estimated that a magnetic potential difference of 590 would be required between the end faces of the magnet bars.

Having ascertained the two factors of the magnetic requirement, the maximum economy of steel was aimed at in determining the length and total sectional area of the permanent magnet. The magnet being divided into two halves, arranged in parallel one on each side of the armature, each half constitutes two magnet limbs on either side of a neutral section situated midway between the ends of the half magnet. The estimated leakage from limb to limb being a very small proportion of the total flux in the half magnet, the flux density varied very little between the neutral section and the ends of the magnet bars. Hence it was found possible to obtain an average energy product for the whole magnet, not much less than the maximum product $\beta_e\phi_e$ for the magnet steel which it was intended to use, and the magnet closely approached the economy of an ideal magnet.

As a result of the inevitable mishaps which attend the construction of the first machine of a new pattern, the actual dimensions of the completed generator were found to differ from the drawings in one or two places, and the final forecast of the flux in the armature was therefore based on the measured dimensions in order to avoid confusing errors of workmanship with errors in predetermination. Leakage conductance from one limb to the other, for each half-magnet, was ascertained by means of the spherical pole formula. In the case of an armature core in which the flux density in the teeth attains a high value, it is naturally impossible to treat the terminal conductance as a constant. The total conductance of the path traversed by the useful flux from pole-piece to pole-piece was therefore estimated for a suitable range of values of flux density in the core teeth, and a curve drawn connecting useful

TABLE 3.

Description of Permanent Magnet	Magnetic Quantity Pre-determined and Verified	Pre-determined Value	Observed Value	Percentage Discrepancy
Small bent magnet with pole-pieces, Fig. 14	Field in air-gap between pole-pieces	1 970	1 950	1·0
Magnetic circuit of a Megger Testing Set, Fig. 15	Flux in armature of generator	44 500	41 400	7·0
	Field in air-gaps of ohmmeter	2 550	2 500	2·0
Field magnet of a magneto-generator, Fig. 16	Flux in armature	197 100	192 000	2·6

Comparison between predetermined and realized values for three ordinary permanent magnets. Step-by-step integration employed in each case. Average discrepancy 3·2 per cent.

flux with terminal potential difference. Three integrations in six steps gave a corresponding curve connecting useful flux provided by the field magnet with potential difference maintained between the pole-pieces by the magnet; and the point where these two curves crossed indicated the predetermined value of the flux in the armature. As the result of the small errors in dimensions referred to above, the forecast differed a little from the flux on which the design had been based.

These three examples have been chosen from a number of instances of predetermination, because the forecast was in each case founded solely on the dimensions of the magnet, those of the apparatus, and the demagnetization curve of a sample of the magnet steel; no assistance being derived from previous experience of similar types. Previous experience of so common a type as the bent magnet was naturally available, but it was not used in the present case; the little bent magnet being treated in all respects as though it had been a novel type. Previous experience in the other two cases was entirely wanting. These three predeterminations therefore afford a good illustration of the kind of accuracy which may be expected in practice, and it will be seen from the figures in Table 3 that notwithstanding an unduly large discrepancy in one case, the average difference between the estimated and the observed values is only a little more than 3 per cent, the estimate being in excess of the realized value in every case.

(34) An Experimental Proof.

Since in practice it is only possible to ensure approximate identity between test-piece and magnet, such comparisons as those just given necessarily include errors which cannot be properly attributed to the method of predetermination. To obtain a comparison entirely free from errors arising from any want of identical conditions as regards the steel in the sample and that in the magnet, an experimental magnet was devised which could be made to do double duty; first acting as the test-piece from which the demagnetization curve would be obtained, and then playing the part of a permanent magnet for comparison between forecast and performance. In this way all doubt as to identity of chemical composition, molecular state and hardness would be removed.

The experimental magnet was in the form of a circular ring of rectangular cross section, and the requirement was assumed to be the maintenance of a magnetic flux in the air-gap formed between the parallel end faces of the severed ring. The magnet was forged from a bar of magnet steel and machined to an accurately circular shape of uniform cross section, the end faces being planes at right angles to the magnetic axis. After machining, the ring was placed in a clamp and hardened in the ordinary way. The ring was then fitted on the internal and external peripheries with thin brass straps, so arranged that by means of screws the air-gap between the magnet ends could be adjusted to any width, from zero up to the amount permitted by the elasticity of the steel.

First treating the hardened steel ring as the test-piece, it was wound with magnetizing and secondary coils for making the customary ballistic test, the air gap being eliminated by screwing the tension strap until the end faces were in close contact. In this condition the steel was carried through a number of maximum magnetic cycles, and a complete series of observations of flux density and applied magnetomotive force was obtained from the final cycle. The observed values having been duly corrected for the small error arising from the presence of the joint formed by the end faces in contact, the demagnetization curve shown in Fig. 17 was plotted from the corrected observation and formed the basis for predetermination. From this curve figures were obtained for plotting the derived curve, shown in Fig. 18, connecting ϕ with the ratio β/ϕ.

The coils used for the ballistic tests having been removed, the ring, in the fully-magnetized state, was then investigated as a permanent magnet; complete

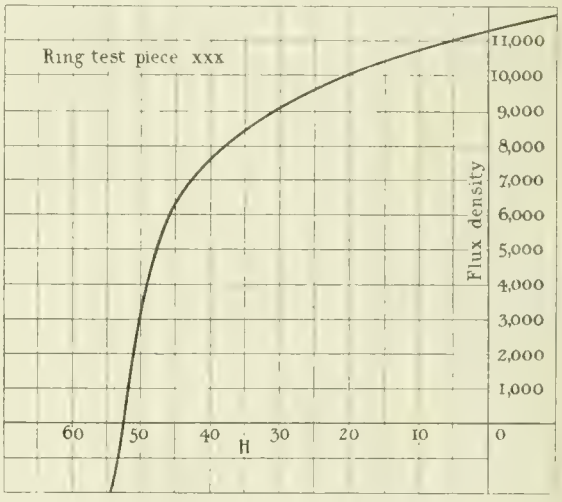


Fig. 17.—Demagnetization curve obtained from the experimental ring magnet as a test-piece.

experimental data being obtained as to flux in the steel, variation of flux density along the length of the magnet, and flux traversing the air-gap. For this purpose a movable search coil had been linked with the magnet, the brass straps and their screw adjustments having been so arranged that the movable coil could slide freely round the ring between the neutral section and the air-gap. Other search coils were provided which could be inserted in, and withdrawn from, the air-gap to measure the flux there. Observational data were obtained with the air-gap adjusted to a number of different widths from zero up to the limiting width.

Predetermination was carried out both by the approximate method of the ratio equation and by step-by-step integration. In the absence of previous experience of ring-shaped magnets, the basis on which to estimate leakage conductances required careful consideration. As a preliminary, lines of force were sketched, freehand, on a drawing of the ring, as shown in Fig. 19, to serve as a mental aid. The length of the steel ring being 25·3 cm., and the perimeter of

the section 3·6 cm., making the virtual diameter D = 1·14 cm., the dimension ratio L/D is about 22, and the conductance factor of an ellipsoid of the same ratio being 1·11 it might be assumed that round about two corresponding zones might be regarded as elementary zones in two parallel cylinders tangential to the magnetic axis of the ring. Reckoned in this way the value of q at $s\,s$ was found to be 1·18, this figure

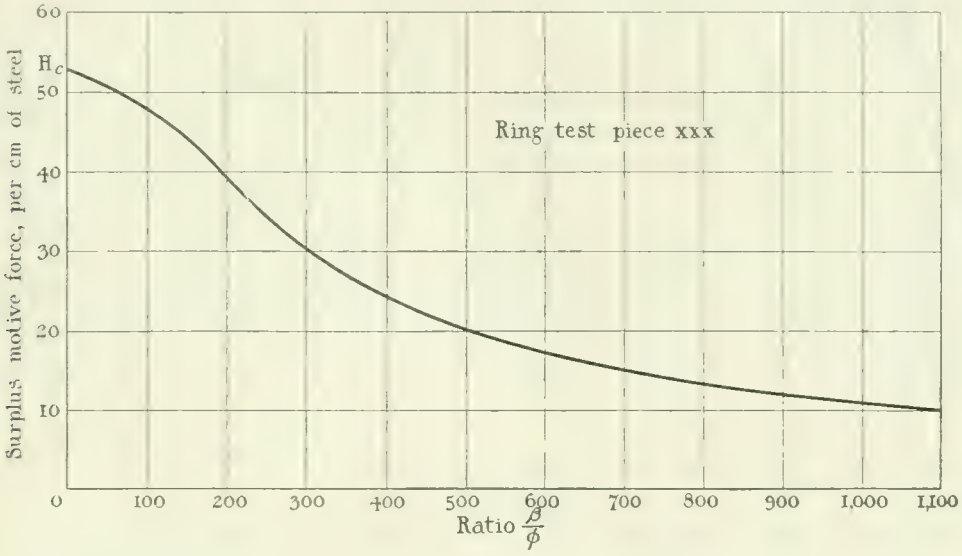


FIG. 18.—Curve derived from Fig. 17, showing the relation between the ratio β/ϕ and the surplus motive force ϕ, for the steel of the ring magnet.

the neutral section of the ring magnet $q = 1·11$ would be approximately correct. On the other hand, reckoning by the spherical pole formula $q = 1·13$. Assuming

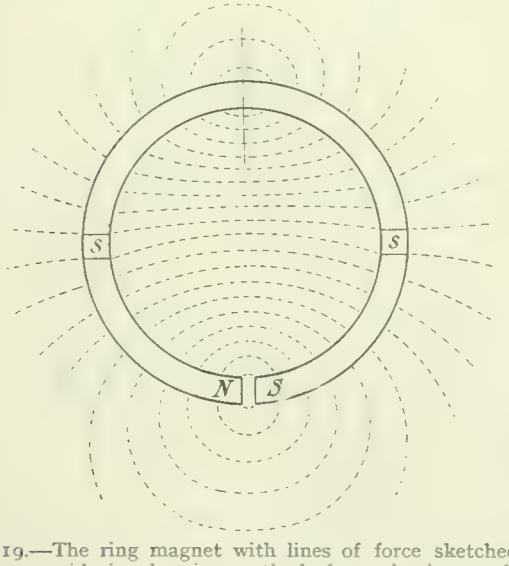


FIG. 19.—The ring magnet with lines of force sketched in as a guide in choosing methods for reckoning conductance factors. Length of magnet 25·3 cm., section area 0·761 square cm.

either value to be taken, the question was how far round the ring on each side of the neutral section q might be treated as roughly constant. A convenient criterion was found in the value of q for the opposite points $s\,s$ (Fig. 19) half-way round the ring. Here being based on the assumption that the elementary leakage path is in a plane normal to the axes of the two cylinders, and that the boundaries of the path are parallel surfaces. Neither assumption is justified in the present case because owing to the transverse pressure * created by the strong field in the neighbourhood of the air-gap, the path between the zones $s\,s$ is not only curved but compressed at the same time, and the increase in length and decrease in sectional area must somewhat diminish the conductance. Hence, it seemed clear that for two zones half-way round the ring q would be something less than 1·18, and it might safely be assumed that anywhere between the neutral section and the half-way points q would have some reasonably constant value lying between 1·11 and 1·18.

The conductance of the fringe paths in the neighbourhood of the air-gap was next considered. Using the formula $q = 2\pi/(\rho + z)$, given in the Appendix, a number of values were calculated for gradually increasing distances from the air-gap. The magnitude of q falls off with great rapidity according to a law of hyperbolic type as the distance from the gap increases, and it was found that for the half-way points $s\,s$ the fringe formula made $q = 1·00$. Assuming the fringe formula to be applicable so far from the air-gap, four values for the conductance factor, anywhere round the ring not too close to the air-gap, had now been obtained by different methods, namely 1·11, 1·13, 1·18 and 1·00, the average value being $q = 1·10$. To err on the safe side the spherical pole value, $q = 1·13$, was taken as the basis for reckoning the conductance of

* CLERK MAXWELL, loc. cit. vol. 2, art. 624, where the effect is likened to "hydrostatic pressure."

leakage paths between pairs of zones round the ring, beginning with those adjacent to the neutral section and ending at zones 8 cm. on either side of it. At this distance it was found that the conductance factor reckoned from the fringe formula also had the value 1·13, so that by taking fringe formula values for q from the 8 cm. points round to the air-gap, the variation of the conductance factor round the ring was made to take place without a break; being constant from the neutral section to the 8 cm. distance, and varying according to the law of the fringe formula from there to the air-gap.

The steps taken to arrive at an estimate for the conductance factor at any point round the ring magnet, have been described at length because the procedure illustrates very well the nature of the artifices which must often be resorted to in cases of doubt. It may be remarked that the ring magnet is by far the most troublesome case the author has come across so far, not merely because there was no convenient

TABLE 4.

Effective Width of Air-gap (cm.)	Terminal Flux		Percentage Discrepancy
	Predetermined by Ratio Equation	Observed Value	
zero	—	8 600	—
0·00035	7 820	7 970	1·9
0·0312	5 920	5 730	3·0
0·0908	3 860	3 812	1·2
0·148	2 830	2 938	3·7
0·211	2 230	2 395	7·0
0·268	1 890	2 050	7·8

Experimental ring magnet. Comparison between terminal flux predetermined by the ratio equation and the same quantity observed by search coil and galvanometer. Average discrepancy 4·1 per cent.

formula for q which could be applied to a ring, but also because the conductance factor varies in magnitude over such a wide range when pole-pieces or their equivalent are entirely absent, a difficulty to which attention has already been drawn.

Once the question of the methods to be adopted in estimating conductance factors had been settled, the rest was solely a matter of simple arithmetic—and patience. Curves having been drawn giving q in terms of x, the distance from the neutral section, for various widths of air-gap, the area of the curves (measured by planimeter) gave the integral $\int_0^{\frac{1}{2}L} q\,dx$; that is to say the aggregate conductance k_c from one limb of the magnet to the other. The conductance of the air-gap was reckoned on the assumption that the ratio area divided by gap-width represents the true value nearly enough. This ratio was therefore treated as the conductance k_u of the path traversed by the useful flux, a quantity which in the present case is the same as the terminal flux. The terminal potential difference for each of six widths of air-gap was then ascertained by means of the ratio equation:

$$\frac{\beta}{\phi} = \frac{L}{A}(k_u + \alpha k_c)$$

In the absence of any knowledge of the precise value of the coefficient of k_c it was assumed that $\alpha = \frac{1}{2}$, the value it has in an ellipsoid. Having determined β/ϕ from the known dimensions L and A, and estimated conductances k_u and k_c, the estimated value ϕ_a for the average surplus force was obtained from the derived curve given in Fig. 18, and in this way the value of the terminal potential difference was ascertained. The quantity to be predetermined, namely, the terminal flux, or useful flux, which passes from one end face to the other across the air-gap, is of course $\phi_a L k_u$. In this way a number of corresponding values of width of air-gap and terminal flux were predetermined, for comparison with the values obtained experimentally. The comparative figures and percentage discrepancies are given in Table 4.

These comparisons are rather favourable examples

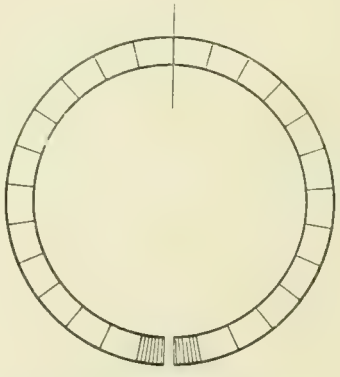


FIG. 20.—Predetermination of ring magnet by step-by-step integration. Method of subdivision into 12 pairs of leakage zones 1 cm. in length, 6 pairs 0·1 cm., and one pair 0·05 cm. in length. Width of air-gap 0·148 cm.

of forecasts made by means of the ratio equation, the discrepancy more often being over than under 5 per cent. The large discrepancies in the two last lines in the table are partly accounted for by the error involved in the assumption that the conductance of an air-gap is equal to the ratio area/width; in other words, that the lines of force in an air-gap are straight lines parallel with the axis. Towards the boundaries of an air-gap the lines of force have a considerable curvature, and if a rough correction for curvature is made in the present case the discrepancies referred to would be reduced to about 4·0 per cent and 4·5 per cent respectively. The error arising in this way rapidly diminishes in importance as the width of air-gap decreases.

For a more precise comparison, a forecast was made by the method of integration, taking as an example an air-gap width of 0·148 cm. For this purpose the magnet limb, of length 12·65 cm., was divided into 12 equal zones of 1 cm. each, beginning at the neutral section (see Fig. 20), followed by 6 zones of 0·10 cm.

each, and ending with a zone 0·05 cm. in width. These very short zones near the air-gap were rendered necessary by the extremely rapid increase in q in the last few centimetres; but 1 cm. zones over the greater part of the limb were only adopted for arithmetical convenience, and they might well have been two, or even three or four cms. in length, so far as accuracy of forecast was concerned. With this sub-division and making use of the values for q already ascertained, three integrations were carried out, ϕ being read from the demagnetization curve given in Fig. 17. The choice of an initial value for β_1 was made by noting first that the flux density corresponding with the average surplus force (already estimated by the ratio equation) was about 9,900; and next, that the maximum remanent density (Fig. 17) was 11,300. It was plain that the density at the neutral section must fall somewhere between these two values and, since it is always good practice to begin with a flux density on the high side, $\beta'_1 = 11{,}000$ was chosen as the starting point of the first integration. This resulted in a terminal ratio $B'/V' = 12{\cdot}4$ as compared with $k_t = 5{\cdot}14$ for the particular width of air-gap. The second integration was therefore carried out from a lower initial flux density, namely $B'''_1 = 10{,}500$. This having resulted in too small a terminal ratio, namely $B'''/V''' = 1{\cdot}70$, the third integration was started from $\beta''_1 = 10{,}750$. The figures obtained from these three integrations are given in Table 5.

Table 5.

Serial Number of Integration	1	3	2
β_1, or flux density at neutral section, denoted by: β'_1, β''_1 and β'''_1 ..	11 000	10 750	10 500
Terminal flux, B′, B″ and B‴	4 940	2 820	1 205
Terminal potential difference, V′, V″ and V‴	399	583	709
Terminal ratio, $\frac{B'}{V'}$, $\frac{B''}{V''}$ and $\frac{B'''}{V'''}$	12·4	4·84	1·70

Figures resulting from three step-by-step integrations along the limbs of the ring magnet shown in Fig. 20.
Length of steel along magnetic axis, 25·3 cm.
Width of section, 1·12 cm. Thickness, radial to the ring, 0·679 cm.
Sectional area of steel, 0·761 sq. cm.
Distance between end faces of magnet, plus equivalent width of "joint," * 0·148 cm. Conductance of air-gap reckoned as being $k_u = 0{\cdot}761/0{\cdot}148 = 5{\cdot}14$.

The tabular figures for β', β''_1 and β'''_1 and the corresponding terminal ratios B'/V', B''/V'' and B'''/V''' having been plotted as co-ordinates, the graph shown in Fig. 21 was drawn, which determines the flux density at the neutral section corresponding with any terminal ratio or terminal conductance. Similarly, the second graph shown in the figure was obtained by plotting the three tabular potential differences V′, V″ and V‴ with the terminal ratios as co-ordinates. Inspection of these two graphs shows that for an air-gap of conductance 5·14 the flux density at the neutral section would be 10,770 and the terminal potential difference 573. Hence, the terminal flux, which is, of course, $k_t V_t$, would be $5{\cdot}14 \times 573 = 2{,}945$ lines. In Table 6 these predetermined values are set alongside the corresponding quantities ascertained experimentally by search coil and galvanometer. Terminal potential difference was, however, not directly observed, the experimental value given in the table having been computed by first deriving a curve for surplus force from the observed variation in flux density along the magnet, and then integrating the curve so obtained by a planimeter. Hence, the tabular figure for "observed" terminal potential difference includes all the errors inherent in the roundabout process by which it was ascertained, in addition to observational errors.*

Notwithstanding the difficulty of estimating the conductance of leakage paths in the case of a magnet of ring shape, accentuated by the absence of pole-pieces, the agreement between the values predetermined by the method of integration and those obtained experimentally is exceedingly close, the discrepancies being well within the limits of observational error.

Having ascertained the flux density at the neutral section by means of the three integrations, the estimated value so determined, namely 10,770, was used as the starting point of a fourth integration in order to obtain intermediate values for flux density and potential difference for a number of points along the magnet limbs. From the figures so obtained the curves shown in Fig. 22 have been drawn, showing the gradual falling off in flux density and the accumulation of surplus force as a growing potential difference, from the neutral section to the end of the magnet; these predetermined curves relating of course to the ring magnet with an air-gap of width 0·148 cm. and estimated conductance 5·14. In this diagram the experimental values for flux density obtained by sliding the movable search coil along the magnet, are shown as plotted points, and the substantial identity of predetermined and

* See Ewing, loc. cit. chap. x, § 162, magnetic resistance of joints.

* Magnetic testing would be much less difficult than it is, if some convenient and universally applicable means for making direct measurements of magnetic potential differences were available; the magnetic analogue of the voltmeter is badly needed.

observed values is apparent. Fig. 22 forms a complete diagram for the ring magnet, and should be compared with that already given in Fig. 12 for an ellipsoid magnet. It will be seen that the lack of uniform

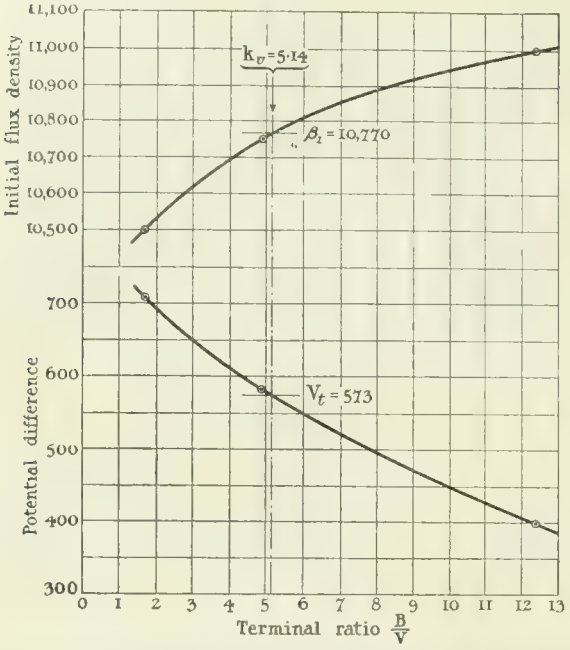


FIG. 21.—Predetermination of ring magnet. Graphs drawn through points plotted from the data given in Table 5, illustrating the method used for determining the flux density at the neutral section and the terminal potential difference.

density entirely changes the character of a magnet diagram.

The experimental proof afforded by this investigation goes to show that when errors arising from want of identity between the test sample of steel and the steel of the magnet are entirely eliminated, the accuracy of the method of step-by-step integration is much more than sufficient for purposes of design and forecast. The figures given in Table 3 for ordinary magnets, predetermined by means of demagnetization curves obtained from samples of steel taken from the bulk, more fairly represent what happens in practice, and the persistence with which realized values fall a little short of the forecast, points to the magnets in bulk never being quite equal to the test pieces in their magnetic quality. The difference is not great, and an addition of about 5 per cent to the terminal flux on which design and predetermination are founded would probably more than compensate for the average want of identity.

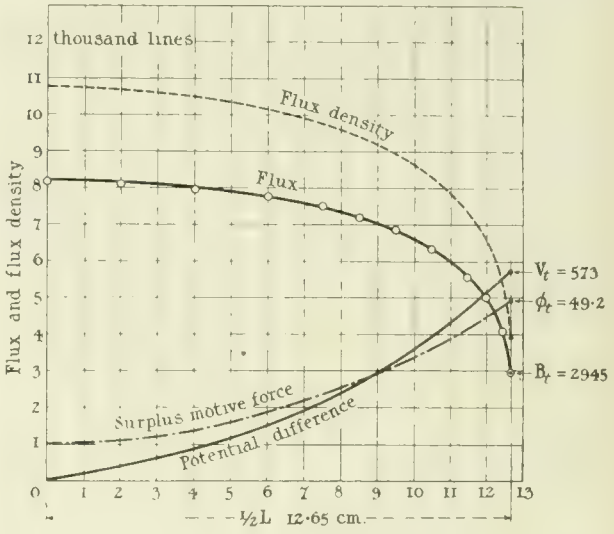


FIG. 22.—Magnet diagram predetermined for the ring magnet with an air-gap 0·148 cm. wide. All the curves are drawn from the series of values obtained in the course of step-by-step integration; the centres of the small circles are values of the flux obtained experimentally by means of a sliding search coil and ballistic galvanometer.

(35) AVAILABLE ENERGY OF MAGNET STEEL COMPARED WITH THE ENERGY OUTPUT OF MAGNETS.

It is instructive to compare the energy output obtained from a permanent magnet with the maximum amount of energy which the same volume of steel could maintain in external space under the ideal condition of uniform flux density. Comparative figures for the four magnets which have been taken as examples of predetermination are given in Table 7, the

TABLE 6.

Magnetic Quantity compared	Value pre-determined by Step-by-step Integrations	Values obtained experimentally by Search Coil and Galvanometer	Percentage Discrepancy
Flux density at neutral section	10 770	10 680	0·85
Terminal potential difference	573	577*	0·70
Terminal flux	2 945	2 938	0·24

Ring magnet (Fig. 20). Comparison between predetermined and observed values; predetermination being carried out by the method of step-by-step integration.

* This figure was computed from the observed variation in flux density.

tabular figures being magnetic energy in ergs. The figure for the maximum possible energy from the given volume of steel is, of course, the maximum value of $\beta\phi$ multiplied by the volume of the magnet and divided by 8π; $\beta_e\phi_e$ being taken from the demagnetization curve used in making the forecast for the particular magnet. The figures for the output of the magnet and the useful energy are derived from the observed quantities obtained by search coil and galvanometer. Hence the comparison is one between what the steel might do under ideal conditions and what it actually does in practice. The proportion the actual output bears to the possible output naturally increases with the power of the magnet, for much the same reason as the efficiency of dynamos increases with their power, but the high proportion attained in the field part in settling its dimensions, and the ring affords a good example of the rule-of-thumb magnet. The same useful energy might easily have been obtained from a little more than half the weight of steel, if economy had been aimed at.

(36) The Criterion of Magnetic Quality for Magnet Steels.

The maintenance of a certain quantity of magnetic energy in space, being the useful function of every magnet, the available energy of a unit volume of magnet steel is the natural criterion of merit. In an ordinary magnet of uniform sectional area, whether designed for economy of steel or not, there is an unavoidable variation in flux density between the neutral section and the ends. The total external energy which

Table 7.

Total Possible External Energy which might be maintained by the Volume of Steel in a Magnet, compared with the Energy actually delivered at the Ends of the Magnet and the Energy utilized.

Description of Magnet	Effective Volume of Steel in the Magnet, cubic cm.	Total Possible External Energy $\frac{\beta_e\phi_e}{8\pi} \times$ Volume, ergs	Actual Energy deduced from the Observed Flux		Proportion to $\frac{\beta_e\phi_e}{8\pi} \times$ Volume	
			Delivered, ergs	Utilized, ergs	Delivered, per cent	Utilized, per cent
Bent magnet with pole-pieces, Fig. 14 . .	19·32	264 000	204 000	103 000	77	39
Field magnets of Megger Testing Set, Fig. 15	214	2 810 000	2 481 000	1 291 000	88	46
Field magnets of magneto generator, Fig. 16	400	5 240 000	4 740 000	4 020 000	90	77
Ring magnet; air-gap 0·148 cm., Fig. 20	19·25	234 100	67 000	67 000	28	28

magnet of the magneto generator (Fig. 16) is not entirely the result of increased size. Something must be credited to the essentially economical nature of the design, which by reducing leakage from the magnet limbs to a relatively insignificant amount, brought the unavoidable variation in flux density in the steel (above and below the economic value $\beta_e\phi_e$) within a very narrow range, and in that way a remarkably close approach to the economy of an ideal magnet has been reached. The little bent magnet (Fig. 14) was designed with equal care for economy of steel, but in this example the pole-pieces, which constitute the apparatus with which the magnet is used, waste in leakage nearly half the energy delivered by the magnet. The ring magnet (Fig. 20) was made of convenient dimensions for carrying out the initial ballistic galvanometer tests upon it in its capacity as the test-piece from which the demagnetization curve was to be obtained. Economy of steel therefore played no

the volume of steel in the magnet can maintain is equal to the volume integral of $\beta\phi$, and hence, as the steel is used in an ordinary magnet, the mean available energy per cubic cm. would be $\frac{1}{v}\int_0^v \beta\phi\, dv$. But to take the mean available energy over some specified range of variation in flux density as the criterion of merit for magnet steel, presupposes the range of variation in density to be the same in all magnets; whereas in practice the range of values necessarily varies widely according to the requirements as to terminal flux and potential difference. Hence as a criterion, the mean available energy could never be a standard of universal application. The only practicable alternative as a criterion of merit for magnet steel is the maximum value of the energy product, $\beta_e\phi_e$; and as a standard, the maximum product has the great advantage of being a precisely defined and easily measurable quantity.

It is, moreover, the key to economic design as we have already seen, representing the best that can be done with the steel under the most favourable conditions.

Figures for $\beta_e\phi_e l/(8\pi)$, the maximum available energy in ergs per cubic cm., are given in Table 8 for a number of different kinds of iron and steel. Iron has been included, to mark the contrast with carbon steels as regards available energy. The addition of so little as 0·7 per cent of carbon to iron immensely increases the surplus magnetomotive force—the result, as we suppose, of a gathering together of magnetic molecules into concentrated groups—and the further addition of tungsten brings about another large increase in surplus motive force and available energy. The recent discovery by Professor Honda of an iron-cobalt-carbon-chromium steel which is stated to have a coercive force of about 200, is a very notable advance in the same direction.* On the assumption that the maximum equivalent current, $si\mathbf{N}$, in the new steel does not fall very far short of that in iron, namely about 17,000

TABLE 8.

Maximum External Magnetic Energy per Cubic Cm., $\beta_e\phi_e l/(8\pi)$, for Various Kinds of Iron and Steel.

Material	Condition	Maximum Energy, in Ergs per c.c. $\beta_e\phi_e l/8\pi$	Coercive Force H.
Lowmoor iron	annealed	183	2
Mild steel	hardened	970	7
Pianoforte steel ..	hardened	5 600	41
Silver steel	rolled	2 500	18
Silver steel	hardened	7 900	68
Tungsten steel: (carbon 0·7 %, tungsten 5 %)	annealed	3 000	18
	rolled	5 300	28
	hardened†	13 100	67

amperes per cm., it may be anticipated that with a coercive force of 200 the maximum value of $\beta\phi$ will be something like twice that of good tungsten magnet steel. If that should turn out to be the case, a magnet of the new steel would have less than half the volume of a tungsten steel magnet for the same useful energy; and since it appears that the improvement is one of increased surplus motive force, the saving in volume would be made by a reduction in length to about half the length of a tungsten steel magnet of the same power.

Up to the present time iron has formed the basic material for permanent magnets and improvement has in every instance consisted in some modification of molecular structure which has, in effect, increased the surplus magnetomotive force. On the view advanced in the first part of this paper it is not possible for a magnetic substance to maintain energy in external space in the absence of those bonds of mutual induction by which individual oriented groups of magnetic molecules hold themselves together and preserve their oriented state. Hence, on that hypothesis, the modifications in molecular structure which result from the introduction of carbon and other things must consist in some kind of gathering together of magnetic molecules into groups more or less independent of neighbouring groups; a variation in structure which cannot go on beyond a certain point, because there is an obvious limitation to the possible amount of shrinkage in the spacing of the molecules in the group.

But although it has been natural in the past to make use of the metals which in the normal state possess powerful inherent magnetomotive forces, the choice of material for permanent magnets is not necessarily so restricted. According to present notions every atom must be potentially magnetic, and it may be that future discovery will result in the conversion of a so-called non-magnetic element into a magnetizable substance in which the effective molecular currents will surpass those of iron in their strength. That this is no great stretch of imagination is demonstrated by Heusler's alloy of the typically non-magnetic metals, copper and aluminium, with manganese. The alloy is strongly magnetic, the magnetomotive force of the magnetic molecules, when they have been oriented by an extraneous field of 100 lines, being about one-seventh that of iron molecules under the same condition.

(37) SUMMARY AND CONCLUSION.

In a lengthy paper dealing with a many-sided subject, the thread of logical sequence is none too easily followed and a brief summary will not come amiss. Throughout the paper the underlying purpose has been to gain a clearer view of fundamental matters and to build up a theory of the permanent magnet consistent with present-day knowledge, and readily applicable to the practical problems of design and predetermination.

Looking through Ampère's microscope at what is going on inside the magnet, we have, in Maxwell's phrase, found nothing but electric circuits carrying permanent currents; nothing but a mass of current rings. We have seen that when the current rings have been oriented to an effective angle θ, the mass has a magnetomotive force equal to $4\pi si\mathbf{N}\sin\theta$ per cm. of length measured in the direction of orientation. In the light of Ewing's theory of the interplay of the forces of magnetic attraction which neighbouring magnetic molecules exert on each other, we next turned our attention to the different torques acting on the average current ring. In that way it was recognized that stable equilibrium of the system of current rings as a permanently magnetized or, rather, oriented mass, implied the existence of secondary torques, independent of the torque arising from the general magnetic field or induction β which is created by the motive force $4\pi si\mathbf{N}\sin\theta$. Now, for the creation of a secondary torque, a secondary magnetic field must be present; a field which the current rings must somehow be capable of producing. But with perfect uniformity of spacing between current rings in the mass, no secondary fields

* See British Patent No. 118,602 granted to Sumitomo Chukosho, Ltd., Osaka, Japan.

† Test-piece B 32, J 1 (see Fig. 8).

are possible; the only magnetic fields in such a system being the self-induction field of each individual ring, a field which moves with the current ring and is, therefore, incapable of creating a torque, and the general magnetic field or induction β which creates a torque $\beta s i \cos\theta$. With uniform spacing, in short, there are no vacant, or partially vacant, regions available as local paths for a secondary magnetic flux. Hence it was clear that secondary fields for the creation of secondary torques could only arise as the consequence of some want of uniformity in the distribution of current rings. A little consideration showed that if, in place of uniformity of spacing, the current rings were supposed to be gathered together into more or less detached and independent groups, the mutual induction of each gathering, each concentrated group, would constitute an independent secondary field, giving rise to secondary torques acting on the individual current rings belonging to the group. Here, then, is to be found that independent secondary torque which alone can provide the margin of stability in equilibrium on which permanent magnetism depends for its existence; the secondary torque which has been referred to as the group torque.

We then went on to examine, as well as we were able, the complex nature of the balance between the torque arising from the induction β and the secondary or group torques which arise from the mutual induction field of concentrated groups, both in their primitive self-contained state and in their oriented condition; an examination which showed how small the margin of stability actually is in oriented iron, and even in oriented hardened steel. At the same time another inference was drawn, namely that in coercive force we have a rough indicator of the degree of concentration into independent groups, an indicator of the strength of the bond of mutual induction by which the current rings in a group hold themselves together when in the oriented state. Without that gathering together, and without the resulting capacity to create those secondary torques by which the current rings are able to resist forces tending to destroy their orientation, coercive force would be non-existent.

The next step, since it was intended to treat the permanent magnet as a magnetic circuit, was to consider the relations between magnetomotive force, reluctance, and magnetic flux in a complete flux tube. It was shown that provided the complexity arising from the interdependence of orientation angle, motive force, induction, and group torque, was duly taken into account, the principle of Ohm's law could be applied to the magnetic circuit; and the origin of the potential difference which maintains the flux in the inert part of the circuit (the part containing no inherent motive force) was found inside the mass of current rings; just as the source of the potential difference between the ends of an inert resistance in an electric circuit lies inside the battery or other generator. The same principle applies in both cases: Everywhere inside the generating part of what has been referred to for convenience as an extended circuit, there is a motive force in excess of what is needed there to maintain the flux or current; and the accumulation of this unexpended excess, or surplus motive force, becomes available outside the generating part of the circuit as a potential difference acting on the external part of the circuit, being expended there in maintaining the flux or the current, in the inert reluctance or resistance.

The condition which gives rise to a surplus magnetomotive force being the diminution of flux caused by the addition of inert reluctance, it was shown that the surplus motive force set free in this way must necessarily be equal in magnitude to the extraneous motive force which would be required to diminish the flux to the same extent in a self-absorbed circuit; that is to say in a circuit containing no external reluctance. And on this numerical equivalence the predetermination of permanent magnets is founded.

The foregoing considerations lead us to regard surplus magnetomotive force, and its origin inside the steel, as the key to an understanding of the way a permanent magnet works; the surplus motive force ϕ being that part of the inherent magnetomotive force generated by 1 cm. length of oriented steel, which enables a magnet to maintain a magnetic field in external space. Surplus motive force is therefore one of the factors of the external energy maintained by a unit cube of magnetized steel, the force factor, and it might be so defined.

In the second part of the paper the two fundamental equations of the permanent magnet were obtained, namely the energy equation $\mathrm{BV} = \beta\phi . \mathrm{LA}$ and the ratio equation $\frac{\beta}{\phi} = \frac{\mathrm{L}}{\mathrm{A}}(k_u + k_p + \alpha k_c)$. This was followed by a discussion of the ellipsoid magnet, an example from which a useful formula was derived for estimating leakage conductance between the limbs of permanent magnets. Finally, the basis for economic design was indicated and alternative methods were described in detail for predetermining the two factors of the energy output of a permanent magnet, terminal flux and potential difference; each method being illustrated by examples from the author's practice.

In conclusion we may hark back once more to the property possessed by a mass of oriented magnetic molecules, which enables a permanent magnet to maintain a magnetic field in external space. In an ideal magnet of uniform flux density, having a length L and forming part of a complete flux tube, the total magnetomotive force $4\pi s i \mathbf{N} \sin\theta . \mathrm{L}$ acting in the flux tube or circuit may be regarded as made up of the sum of two terms $f\mathrm{L}$ and $\phi\mathrm{L}$. Each has its allotted task; $f\mathrm{L}$ being expended in maintaining the flux inside the steel, and $\phi\mathrm{L}$ being available for expenditure in the inert reluctance which completes the flux tube outside the magnet. This division into two portions may be carried one stage further back, and in imagination we may see the orientation angle θ made up of the addition of two angles θ_f and θ_ϕ, so that the total magnetomotive force might be written $4\pi s i \mathbf{N} \sin(\theta_f + \theta_\phi)\mathrm{L}$. Here the orientation θ_f gives the mass of current rings sufficient motive force (and no more) to maintain the flux in the steel, and θ_ϕ is an additional deflection beyond that orientation; a superposed deflection which is brought about by the torque created by the

secondary field arising from the mutual induction of the concentrated groups. In other words, the orientation angle of the average current ring in the oriented mass is in excess of what is needed to maintain the flux in the compartment of space occupied by the magnetic molecule which the current ring represents, and since the excess in orientation angle is brought about by the local or mutual induction field of the group, the group torque may be regarded as compelling the individual current ring to generate a surplus magnetomotive force by holding it at an angle which it could not otherwise maintain. In this way, the source of the factor ϕ in the energy product $\beta\phi$ is finally traced back to the action of the local field of the concentrated group, on the individual current rings which form the group. But local fields of mutual induction capable of acting in that way require vacant spaces for their propagation, and they can only come into existence as the result of some departure from uniformity which leaves suitable local regions of space more or less free for them.

Hence the gathering together of molecules of equal magnetic moment into concentrated groups, need not be regarded as the sole possible mode of departure from uniformity which will endow the mass with the necessary power to form local bonds of mutual induction. Any kind of molecular *variformity* which, in effect, brought about an unequal distribution of the elementary magnetomotive forces, would give rise to a similar state of things. And in view of the fact that iron is found to possess an increased ability to maintain itself in a partially oriented state when carbon and other non-magnetic substances have been introduced, it seems by no means unlikely that the necessary departure from uniformity may consist in the congregation, in one mass, of equally spaced molecules possessing unequal magnetic moments; some stronger, some weaker, than the average. As a limiting case, we may imagine the presence of non-magnetic molecules distributed throughout a mass of magnetic molecules. Such an arrangement would provide magnetically vacant spaces for the propagation of local fields of mutual induction, in much the same way as the concentrated groups which we have taken as a simple example of variformity.

As a corollary to Ewing's theory, the hypothesis of molecular variformity appears to be necessary to account for the facts and even for the very existence of permanent magnetism. It stands or falls with that theory of course, but as a tentative explanation of the ability of a permanent magnet to maintain a magnetic field in external space, it may serve a useful purpose in guiding our thoughts until an ampler knowledge of the world of atoms gives us something better.

[Note.—The detailed verifications of the experimental ring magnet (Fig. 20) and the bent magnet (Fig. 14) were made by Mr. Finnis in the experimental laboratory at Acton-lane Works. The two magnets, Figs. 15 and 16, were verified by tests carried out in the Works by Mr. Clark and Mr. Baker. In addition, a very large amount of unrecorded experimental work has been necessary in connection with the present paper, much of it consisting in the investigation of various troublesome side issues which could not be left unexplored. The whole of this work has been carried out by Mr. Finnis with his accustomed skill. On the practical side the author has taken advantage of friendly offers of help from various sources; acknowledgment of these will find its due place in the succeeding paper treating of permanent magnets in the making.]

APPENDIX.

On the Estimation of Magnetic Conductance.

The value of any magnetic conductance or reluctance depends, of course, on the shape and dimensions of the path or flux tube; and since the shape of the flux tube is that assumed by the lines of force which form its boundaries a strict determination of conductance, based on first principles, should begin by deducing the configuration of the lines of force from the properties of the magnetic medium. But the problem so stated has not been solved, and our notions about the configuration of lines of force in magnetic fields have been derived partly from the calculable effect of hypothetical magnetic poles, acting at distant points in space without the intervention of a transmitting medium, and partly from the visible behaviour of iron filings in a magnetic field and the tracing of lines of force by means of a compass needle. In these ways, aided by prolonged experience, we have acquired a general knowledge of the way lines of force will go, and the formulæ used for estimating magnetic conductance are based on the assumption that artificial lines of simple geometrical forms may be substituted for the actual lines of force which follow complicated laws of curvature, provided the form of the artificial lines bears some sort of resemblance to the actual configuration of the magnetic field. On the principle of maximum energy, a magnetic field naturally arranges itself for maximum conductance, and hence the substitution of artificial lines of force, which tends to introduce unnatural restrictions, must in general lead to an underestimate of conductance; but provided the artificial lines roughly represent the real configuration, the substitution does not lead to prohibitive errors. These remarks seem called for by way of warning, because formulæ such as those given below have an impressive appearance which is not justified by their origin. However learned they may look, they are only fit for estimating purposes; their accuracy being limited by their hypothetical and empirical basis.

It will be convenient to take the different conductances in the order in which they are naturally dealt with in the course of design or predetermination, beginning with an air-gap; then taking the fringe paths which lie outside the boundary or edge of the gap; next considering the conductance of the space occupied by the stray field created by the pole-pieces, or by the polar portions of the magnet limbs; and lastly taking the leakage paths between the limbs of the magnet.

Air-gaps.

When the polar surfaces forming the opposite faces of the gap are flat, as in Fig. 23, the conductance of the gap is approximately :

$$k = \frac{w s}{g}$$

It should be remembered that this formula takes no account of the pressure in the magnetic medium transverse to the lines of force. The transverse pressure causes the lines to bend outwards as the edges of the gap are approached, and hence the conductance of the path actually traversed by the flux which passes from one polar surface to the other is somewhat greater than that given by the formula. When g is as much as one-tenth of s or w this effect begins to be noticeable, and it so rapidly increases with increasing gap width, that when g is one-fifth of s or w the conductance will

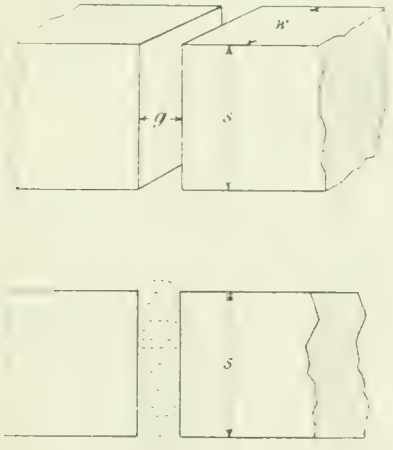


Fig. 23.

be roughly 4 or 5 per cent greater than that estimated by the formula.

For an air-gap between cylindrical surfaces as in Fig. 24 the conductance is :

$$k = \frac{w\theta}{\log_e(1 + g/a)}, \quad \theta \text{ being in radians.}$$

It may be noticed that when g/a is small, say 0·02 or

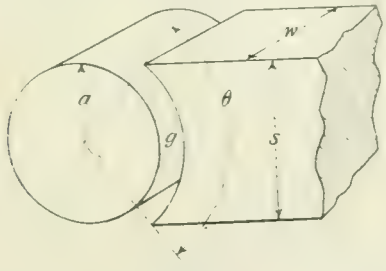


Fig. 24.

less, $\log_e(1 + g/a)$ is nearly equal to g/a, and the formula then reduces to :

$$k = \frac{w a \theta}{g}$$

which is the simple form : area divided by gap-width.

Conductance of Fringe Paths originating on Flat Surfaces.

The conductance of the fringe path at the boundary of an air-gap between rectangular pole-pieces of width w, is roughly :

$$k = \frac{w}{\pi} \log_e\left(1 + \frac{\pi x}{g}\right)$$

when the flat polar surfaces which form the beginning and end of the path lie in the same plane, as in Fig. 25. This formula, which was introduced by Forbes in the early days of the dynamo, considerably underestimates the conductance. Mr. Finnis has recently suggested that a closer approximation would be obtained by supposing the lines of force to be portions of confocal ellipses as shown in Fig. 26 ; the foci $f f$ for all lines of force in any plane normal to the polar surfaces being at the edges of the air-gap. Mr. Finnis's formula

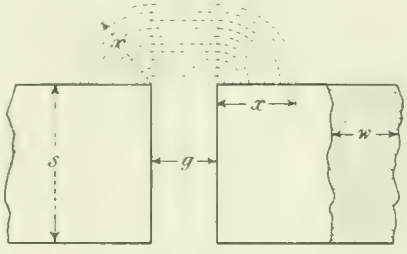


Fig. 25.

for an elliptical fringe on flat polar surfaces of width w is :

$$k = \frac{w}{\pi} \log_e\left[1 + 2\frac{x + \sqrt{(x^2 + xg)}}{g}\right]$$

The elliptical lines imitate the effect of the transverse pressure in squeezing the lines of force outwards, and

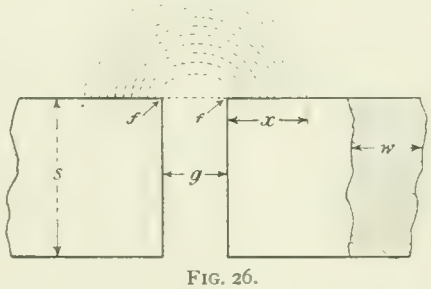


Fig. 26.

for that reason the formula gives a closer approximation to the actual conductance than the Forbes formula.

Fringes originating on Cylindrical Surfaces.

When one or the other of the above formulæ is applied to the four surfaces of a rectangular pole, the whole fringe conductance is considerably underestimated because no account is taken of the wedge-shaped spaces available in the neighbourhood of each edge where the flat surfaces meet. To include these vacant spaces the author has extended the Forbes formula to the case of a fringe originating on either side of an

air-gap formed between the flat ends of two coaxial cylinders. The elementary leakage path is then a hollow shell, as shown in Fig. 27, and the conductance per cm. of zone width is:

$$q = \frac{2\pi}{\rho + z}$$

Here $\rho = \frac{g}{a + x}$; so that, putting $x = n\,a$, $\rho = \frac{g}{a(n+1)}$

$$z = \frac{4n}{\sqrt{(1-n^2)}} \tan^{-1}\sqrt{\left(\frac{1-n}{1+n}\right)} \quad \text{when } n < 1$$

$$z = 2 \quad \text{when } n = 1$$

and $$z = \frac{2n}{\sqrt{n^2-1}} \log_e [n + \sqrt{(n^2-1)}] \quad \text{when } n > 1$$

For convenience in computing q from the above formula a table is appended giving values of the quantity z in terms of the ratio n. For practical use a

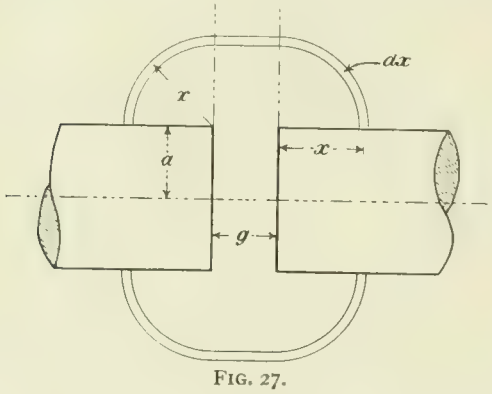


FIG. 27.

curve should be drawn from the tabular figures enabling z to be found by inspection for any value of n.

Table giving z in terms of $x/a = n$; for use in applying the Formula $q = \frac{2\pi}{\rho + z}$.

n	z	n	z
0	0	1·3	2·36
0·1	0·296	1·5	2·59
0·2	0·561	1·7	2·79
0·4	1·013	1·8	2·88
0·6	1·398	2·0	3·05
0·8	1·722	4·0	4·23
0·9	1·859	8·0	5·56
1·0	2·000	16·0	6·92
1·1	2·13	20·0	7·30
1·2	2·25	24·0	7·68

The above formula only gives the conductance per cm. of zone width, and to find the total conductance of a fringe extending for a distance x from the edges of the air-gap, it is necessary to find the value of $\int q\,dx$ or $2\pi\int\frac{dx}{\rho + z}$. This can be done by drawing a curve connecting q with x and measuring its area.

The total conductance of a fringe originating on cylindrical surfaces may, however, be computed from the following formula for which the author is indebted to Mr. Finnis. The assumption made is that the lines of force which form the boundaries of the leakage paths are confocal ellipses, the common foci being located at the edges of the air-gap. As in the case of the elementary leakage path shown in Fig. 27, the elliptical paths take the form of hollow shells surrounding the cylinders. The total conductance of the fringe stated in terms of its extent x on each cylinder and a complicated quantity v, is as follows:—

$$k = \frac{\pi\sqrt{(v^2 - x^2)}}{\cos^{-1}(x/v)} \quad \text{when } v > x$$

$$k = \pi x \quad \text{when } v = x$$

$$k = \frac{\pi\sqrt{(v^2 - v^2)}}{\log_e\left[\frac{x + \sqrt{(v^2 - v^2)}}{v}\right]} \quad \text{when } v < x$$

The quantity v is:— $a \log_e\left[1 + 2\frac{x + \sqrt{(x^2 + xg)}}{g}\right]$,

where a is the cylinder radius.

This formula for the total conductance of a fringe originating on cylindrical surfaces, as also the formula $q = 2\pi/(\rho + z)$, may be used for estimating the conductance of a fringe which extends all round rectangular poles, by substituting for the rectangle a cylinder of the same perimeter. Denoting the sides of the rectangle by s and w, the perimeter will be $2(s+w)$, and hence the radius of the equivalent cylinder will be $a = (s+w)/\pi$.

CONDUCTANCE OF RADIATING LEAKAGE PATHS (EQUIVALENT SPHERICAL POLES).

Apart from air-gaps, leakage paths which can be treated as fringes, and other paths by which induction

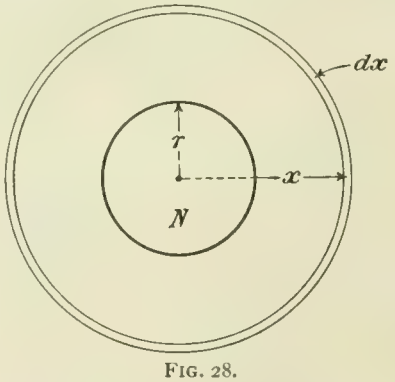


FIG. 28.

passes more or less directly from one pole-piece to the other, there is always a considerable area of the polar surfaces of a magnet system from which lines of force radiate outwards into space, forming what is vaguely defined as a stray field. Whenever lines of force radiate in this way as from a polar point or centre located inside a pole-piece, or inside the limb of a magnet somewhere towards the end, the conductance of the leakage path so formed from pole to pole can be estimated with sufficient accuracy by substituting for the

pole-piece, or the polar end of the magnet limb, a spherical pole of dimensions which make it the equivalent of the actual pole in its leakage-effect.

The conductance of the path extending outwards in all directions from the surface of a spherical pole of iron or steel is found as follows: Referring to Fig. 28, the area of the elementary spherical shell of radius x is $4\pi x^2$ and denoting its thickness by dx the reluctance of the shell is $dx/(4\pi x^2)$. Hence the reluctance of the space between the surface of the spherical pole N of radius r, and a spherical boundary of radius nr will be

$$R = \frac{1}{4\pi}\int_{r}^{nr}\frac{1}{x^2}dx = \frac{1}{4\pi r}\left(1-\frac{1}{n}\right)$$

and if we suppose the boundary to be at some considerable distance from the pole so that n is a large number, $1/n$ becomes negligible and the reluctance of the path extending outwards from the pole N is simply $1/(4\pi r)$. Similarly the reluctance from a distant boundary to a complementary pole of the same radius as N will also be $1/(4\pi r)$. Hence the reluctance of the entire path from pole to pole will be $2/(4\pi r)$, and the conductance from spherical pole to spherical pole will be:

$$k = 2\pi r.$$

It is convenient to express the conductance of the leakage path formed in this way in terms of the surface of either pole. Denoting the surface of the pole by S we have $4\pi r^2 = S$ from which $r = \sqrt{[S/(4\pi)]}$, so that the conductance becomes $k = 2\pi\sqrt{S/4\pi} = \sqrt{\pi S}$; and since $\sqrt{\pi}$ is 1·77, we have:

$$k = 1{\cdot}77\sqrt{S}, \text{ spherical pole to pole.}$$

The conductance of a radiating path, therefore, depends only on the superficial area of the polar surface from which it originates, and the formula may evidently be applied to poles of any shape, subject of course to the essential condition that as regards their form and position they lend themselves reasonably well to polar radiation. That the application of the formula to poles of rectangular shape is legitimate may be shown in an elementary way by considering a pole in the form of a cube of side s. The conductance between two such cubical poles will be greater than that between two spheres of diameter s, but less than that between two spheres of a diameter equal to the diagonal dimension of the cube; since the smaller sphere would lie just inside the cube, and the larger would just envelop the cube, touching it at its corners. Now for the two smaller spheres we have:

$$k = 2\pi.\tfrac{1}{2}s = \pi s$$

and for the larger spheres, since the diagonal of the cube is $\sqrt{3}.s$, we have:

$$k = 2\pi\sqrt{3}.s/2 = \pi\sqrt{3}.s.$$

It may be assumed that the mean of these two conductances will represent the conductance between the two cubical poles quite nearly enough, and hence the conductance from one cubical pole to the other will be approximately:

$$k = \frac{\pi s}{2} + \frac{\pi\sqrt{3}.s}{2} = \frac{1+\sqrt{3}}{2}\pi s.$$

But the surface of the cubical pole is $6s^2$, so that $s = \sqrt{(S/6)}$, and hence $k = \tfrac{1}{2}(1+\sqrt{3})\,\pi\sqrt{(S/6)}$, from which we find:

$$k = 1{\cdot}75\sqrt{S}, \text{ cubical pole to pole;}$$

a value which only differs from that given by the spherical pole formula by a little more than 1 per cent.

For poles other than spheres or cubes, such for example as the limbs of a bar magnet, the radiating lines of force do not proceed from a well-defined internal point but rather from a series of points distributed along the magnetic axis. Hence if we imagine a spherical pole to undergo a gradual change in shape, passing from a sphere to a cube and from that to an elongated body of rectangular, or indeed any sort of elongated form, there will be a gradual departure from strictly polar radiation and a correspondingly gradual departure from accuracy in the estimate of conductance based on the spherical pole formula. The formula is, however, one of very wide application because it is founded on the fact that every magnet has some sort of quasi-polar region at each end (generally rather ill defined) from which lines of force proceed into external space more or less as though they had their origin in a polar point inside the steel. Incidentally it may be remarked that in so far as a polar region behaves like a truly radiating pole, the mechanical force it will exert on a similar pole must necessarily vary inversely as the square of the distance. It was the experimental demonstration of this property in magnets, which in early days gave rise to the idea of a magnetic attractive matter behaving in a strictly Newtonian fashion.

The author has made constant use of the spherical pole formula for many years past, applying it to a wide variety of magnetic problems, from the stray field of dynamos to the flux in compass needles. Its application in the latter case, the case of the ordinary bar magnet, may be explained here because it affords a good example of the limits to which the formula may be stretched for purposes of rough estimation. Treating a bar magnet as a single magnetic circuit, after the manner described in section 25, the conductance of the leakage path from limb to limb, estimated from the spherical pole formula, will be $k = 1{\cdot}77\sqrt{S}$; where S is the superficial area of one limb of the magnet. The position of the effective poles is of course indefinite. In an ellipsoid the distance between them is about two-thirds of the length of the magnet, but in an ordinary bar magnet of uniform section the apparent poles are somewhat further apart and the distance between them may be assumed to be about 0·7 L. On this assumption the effective magnetomotive force of a bar magnet will be about $V = 0{\cdot}7\,L\phi$ and the total flux βA will be

$$\beta A = 0{\cdot}7\,L\phi \times 1{\cdot}77\sqrt{S}$$

from which

$$\frac{\beta}{\phi} = 1{\cdot}77 \times 0{\cdot}7\,\frac{L}{A}\sqrt{S}$$

The ratio β/ϕ being estimated in this way, the derived curve for the magnet steel, giving β in terms of β/ϕ, determines a value of β which may be taken as the flux density at the neutral section. In this way the total flux traversing the neutral section of any ordinary bar magnet may be roughly predetermined, provided the dimension ratio, length divided by equivalent diameter, does not exceed 25 or 30. Beyond that proportion the departure from polar radiation becomes too great and the spherical pole formula no longer serves a useful purpose.

The spherical pole formula may be used to find the average value of the conductance factor q along the limbs of any magnet, by dividing the total leakage conductance from limb to limb by $\frac{1}{2}$ L. Thus:

$$q = \frac{1\cdot77\sqrt{S}}{\frac{1}{2}L} = 3\cdot5\sqrt{\frac{S}{L^2}}$$

But $S = \frac{1}{2}pL$, where p is the perimeter of the magnet bar, and hence for the leakage conductance per cm. of zone width:

$$q = 2\cdot5\sqrt{\frac{p}{L}}$$

It will be seen that in this case, as in that of an ellipsoid magnet, the conductance factor depends not on absolute but only on relative dimensions. The same thing will be found to apply to the conductance factor between parallel cylinders, and consequently between parallel bars of rectangular section. In short leakage conductance per cm. of zone-width depends solely on relative magnitude; solely on shape and not on size.

The Effective Part of a Spherical Pole.

In the case of a bar magnet, lines of force radiate in all directions from the entire surface of the equivalent

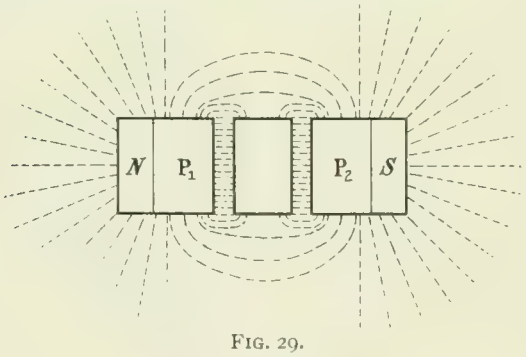


Fig. 29.

spherical pole, but when the magnetic system forms anything approaching a well-defined magnetic circuit, the polar regions are only free to radiate into space external to the enclosure formed by the magnet with its poles and air-gap. In the typical case shown in Fig. 29, something like half the surface of each pole-piece is taken up by the flux in the air-gaps, the fringes across the edges of the gaps, and the fringes which pass directly from one pole-piece to the other. Hence the conductance of the radiating paths from pole to pole would be roughly half $1\cdot77\sqrt{S}$, where S is the entire surface of one pole-piece. It will be noticed that the proportion of space available for radiating paths is only vaguely defined, and some exercise of judgment is therefore required in determining what fraction of the spherical pole conductance should be taken in any particular case. But leakage forming a stray field is usually only a small proportion of the total flux, and hence there is no need for more than a rough apportionment of the conductance given by the spherical pole formula.

Conductance between Parallel Cylinders.

At the author's suggestion Mr. Finnis has obtained the following formula for the magnetic conductance of the leakage path between two parallel cylinders. The corresponding formula for the electrostatic capacity of two parallel cylindrical conductors had previously been obtained by Kennelly. The formula states the conductance between two zones of 1 cm. width; that is to say it gives the conductance factor q for two

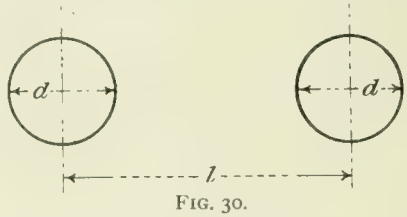


Fig. 30.

cylinders of diameter d, at a distance l between their axes, as shown in Fig. 30.

$$q = \frac{\pi}{\log_e\left[\frac{l + \sqrt{(l^2 - d^2)}}{d}\right]}$$

or putting $l/d = n$,

$$q = \frac{\pi}{\log_e\left[n + \sqrt{(n^2 - 1)}\right]}$$

and when n is greater than 5 this reduces to:

$$q = \frac{\pi}{\log_e 2n} \text{ nearly enough}$$

The following table gives the value of q for values of n from 1 to 20, which covers all the cases of magnets

Table giving Values of Conductance Factor q for Two Parallel Cylinders; $n = l/d$.

n	q	n	q
1·0	Inf.	5	1·37
1·1	7·10	6	1·27
1·2	5·04	7	1·19
1·3	4·29	8	1·13
1·5	3·31	9	1·09
2·0	2·38	10	1·05
3·0	1·74	15	0·93
4·0	1·52	20	0·85

with parallel limbs which are likely to occur in practice. In applying the table (or the formula) to magnets of

rectangular, or any other section, it is only necessary to make:

$$d = \frac{\text{perimeter of section}}{\pi}.$$

Conductance between the Limbs of an Ellipsoid Magnet.

It has been shown in Section (27) that the conductance factor for leakage paths between the limbs of an ellipsoid magnet of circular section is:

$$q = \frac{\pi a^2}{c^2}\left(\frac{4\pi}{N} - 1\right);$$ see page 803,

N being a quantity which depends only on the dimension ratio c/a. The table on this page contains values of the conductance factor computed from formula (31) for dimension ratios from 1 to 100. The tabular figures are intended to be plotted as the co-ordinates of a curve from which q may be ascertained by inspection.

Conductance Factors for Ellipsoid Magnets of Circular Cross Section.

c/a	q	c/a	q
1	6·28	14	1·32
2	3·77	17	1·23
3	2·87	20	1·15
4	2·41	25	1·07
6	1·94	30	1·01
8	1·69	40	0·93
9	1·59	60	0·83
10	1·52	80	0·76
12	1·40	100	0·73

Conductances estimated from Freehand Sketches.

When a leakage path cannot be brought within the scope of a convenient formula, the conductance may always be estimated with sufficient accuracy by making a sketch of the probable course of the induction. In many cases the curvature of the path makes it necessary to break it up into a number of elementary paths. The division should be done systematically by setting off a number of points at equal intervals along the line representing the surface where the path begins, and a corresponding series of points on the surface where it ends. The points on the two surfaces having been joined by lines of force drawn freehand, each elementary path so formed may be measured by running over it with a map measuring wheel, the conductance of each element being reckoned from the dimensions so obtained.

[The symbols used by the author in his paper were the subject of comment in the discussion, and subsequently the Institution Papers Committee had an exchange of views with him as to whether it would be possible to make use of the symbols for flux, flux density and reluctance approved by the International Electrotechnical Commission. The author's view, in brief, is that in presenting the subject of the paper from a novel point of view so many quantities are introduced for which no recognized symbols exist, that it seemed preferable, and even necessary for clear exposition, to make use of a set of symbols co-ordinated for that purpose, although in the three instances referred to these symbols differ from those approved by the International Commission. The notation of the original paper has accordingly been adhered to in the *Journal*.—Sec., I.E.E.]

Discussion before The Institution, 13 May, 1920.

Mr. L. B. Atkinson: This paper will, I feel sure, rank as a classic with those of Hopkinson and Kapp in 1886, where they gave us the means of predetermining the magnetic constants of the dynamo, that is to say, really of the "electromagnet." It is the first published attempt to put forward on a basis usable by engineers a system of design and predetermination of "permanent magnets." The examples given in the paper show that where the path of the magnetic induction is determinable a high degree of accuracy may be arrived at by the author's method. This is that method of reverse summation, i.e. step by step from effect to cause, which has proved so useful in the design of electromagnets and in the determination of wave distortion on long telegraphic and telephonic lines. The author has spoken of the necessity of working with some kind of theoretical basis, and he has given his own physical conception of the mechanism by which the observed results are reached. We must carefully distinguish, however, between the author's results in predetermination and his physical conception. Maxwell in his "Treatise" makes the following remark: "A theory of magnetic matter, if used in a purely mathematical sense, cannot fail to explain the phenomena, provided new laws are freely introduced to account for the actual facts." If therefore we find some points in the author's physical conception which do not appear to fit in with certain experimental facts or well-founded deduction therefrom, it would appear well to examine them, and, if necessary, to modify the physical conception. It is in that connection that I propose to comment on the paper. I am glad that the author has adopted the molecular electron current as the physical basis of magnetism. Electrical engineers are not thinking sufficiently in terms of electrons. Wireless engineers have done so in the last five years, thanks to the thermionic valve, and I urge electrical engineers generally to follow their example. Ampère's theory of magnetism as being due to a molecular current in a perfectly conducting medium of a definite geometric form was considered by Maxwell, but the properties of electric circuits of infinite conductivity formed by a molecular electron orbit, not necessarily of defined geometric form, have not been fully considered

by the majority of electrical engineers. Maxwell on this subject said: "The conception of perfectly conducting bodies leads to results exceedingly different from any phenomena which we can observe with ordinary conductors." I think the author has not sufficiently realized the point. It we turn to page 785, Fig. 2 (I) shows the current rings pointing at random, and the author says*: "The energy of an electric current being kinetic, any two or more current rings will tend to turn on their pivotal axes in directions which will increase their joint energy." That statement is only true if the words are added, "if the currents are maintained constant by an external source of energy," and it was so stated by Maxwell. The author continues: "Evidently the energy of the mass will be increased if any two or more rings turn round until they possess a magnetic axis in common, and so create for themselves a bond of mutual induction." On the contrary, the energy diminishes. In the Tenth Kelvin Lecture which I delivered in 1918† I devoted considerable space to the interaction of two perfectly-conducting circuits, each carrying an initial current, and included a graphical construction for determining the current in the circuits in all positions, also showing that the movement under the mutual electrodynamic forces always diminishes the energy and the current in one or both circuits. If we add no energy but work is done, it must come from the existing energy and thus diminish it. Figs. 1, 2 and 3 and the statement accompanying them are based on what would occur with coils in which currents are maintained constant by a battery. The author quotes Langevin in support of the thesis that the molecular current is a nearly constant quantity, but Langevin's statements I think only relate to the possible variation in the molecular current due to the creation of a magnetic force by an exterior current. I find it impossible to overlook the fact that the changes of relative orientation must involve great changes of molecular current. If that is so, it seems seriously to disturb the basis of the author's conception. That conception is based upon a constant magnetomotive force per molecule in a direction normal to the plane of the molecular orbit, and the addition or subtraction of these magnetomotive forces in a medium of defined magnetic properties with the variation of induction arising therefrom. Is there a substitute? It seems to me that there is. The outstanding property of a perfectly conducting circuit is this: it is impossible to alter the flux threading it except by applying an electromotive force to the circuit. Consequently, in the medium where the molecular currents change their orientation, the induction threading every molecular circuit is always constant, and equilibrium results when the lines of induction are the shortest possible. If a molecular line of induction can shorten by means of any small change in the orientation, the change will take place. If the result of orientation is to increase the length of the line of induction, the orientation will not take place. There may be two positions where the second would give a shorter line than the first, but to reach it an intermediate position must be passed which would lengthen the line; in that case a semi-stability exists, which vibration or heat may upset. A modification of the author's conception as set out in Figs. 2 and 3 along these lines would, I think, be nearer to the truth. But there is an experimental fact which still more strongly enforces the idea that we must remodel the author's conception on the line of the flux being constant in all circumstances throughout the molecular circuit. On page 729 the author considers a magnetized steel ring severed at a cross-section and with the severed ends drawn apart. The "instantaneous effect of the increase in the reluctance," he says, "will be to diminish the flux" in the magnetic circuit. The late Dr. Silvanus Thompson, however, showed an experiment with a horseshoe magnet and removable keeper, and stated that the removal of the keeper makes no change whatever in the total flux passing through the central section of the magnet. This experiment, if correct, indicates that the property of constant flux per molecule is fundamental. It involves, it is true, changes of linear velocity of the electron; this would involve change in the periodic time of rotation, unless the orbit expands and contracts, and as I feel that the periodic time rather than the orbital diameter is constant, I think the variation in diameter probable. I am convinced that the general reasoning in the paper is correct and it has made "permanent magnetism" so clear that I feel the author's conception and mine are probably mathematically equivalent. Nevertheless, I consider that the theoretical part of the paper must be modified so as to accept the constancy of the molecular flux, with its corollary of a varying electron velocity as an integral part. That change will not in the least modify the author's general theoretical view of permanent magnetism, but will involve some change in the interior mechanism which he has described.

(*Communicated*): Since the discussion on Mr. Evershed's paper I have had some exchange of views with him, particularly on the question of the Thompson experiment. Through the kindness of Dr. Eccles, the permanent magnet on which the late Dr. S. P. Thompson experimented was found at Finsbury College, and Mr. Evershed has repeated the experiment with this magnet and with others. The results do not confirm the statement that the flux at the neutral section of a permanent magnet is constant whether the keeper be on or off. I hope Mr. Evershed will add to his paper the result of these experiments, but the deduction which I (in the discussion) drew from Thompson's experiment falls to the ground. But in saying this I still hold to the view that the induction through a molecular circuit cannot be altered, and that Mr. Evershed's conception must take account of this.

Major K. Edgcumbe: The author has said that the subjects of predetermination and design must be treated as two separate sides of the question. As regards *predetermination*, when I turned to the Table on page 811, in which the author states that he can predetermine the performance of his magnets to within 1 or 2 per cent, I was at once a convert to his system. We seem now to be in a position to deal with permanent magnets in much the same way as Hopkinson enabled us to deal with electromagnets. Coming next to the question

* Since corrected. † *Journal I.E.E.*, 1919, vol. 57, p. 1.

of *design*, I am not sure that it is quite so simple as the author would have us believe. He deals throughout with the question of getting the utmost possible magnetic energy out of a given volume of steel; that is to say, he works at that value of flux density which will give him a maximum $\beta\phi$, as he calls it. Is he satisfied that this procedure will give him the required permanence? It has always been considered good practice to keep the reluctance of the air-gap small compared with that of the magnet; that is to say, to use a tall and thin magnet and a short and fat air-gap. The author does not deal with this point, although it is, in most cases, more important than that of the weight and size of the magnet. The matter is, also, complicated by the fact of there being two forms of permanence. There is the permanence required by the magneto manufacturer, for example, whose magnets are subjected to very great magnetic racking, but who does not mind if the permanence falls 5 or 10 per cent. On the other side there is the instrument maker who is anxious that the flux should not fall by more than a fraction of 1 per cent. I should be very glad if the author could give us some information on that matter. I do not at all like the symbols which the author has used. He said that several of the equations are self-explanatory, but I for one should have said that "B" stood for flux density, whereas it represents the total flux. Again, I should have said that "V" represented voltage, but it means "motive force." (Why not magnetomotive force, by the way and have no confusion?) The International Electrotechnical Commission have obtained international agreement upon a number of symbols, and the Institution has given its *cachet* to them. It is most unfortunate that a classic paper should be issued under the ægis of the Institution with symbols entirely different from those universally recognized.

Professor E. W. Marchant: One of the things that has interested me as much as anything has been the possibility which the paper holds out for an improvement in magnetic materials. The author's theory of permanent magnetism as being due to the motion of electrons in the atom is very fascinating. I had hoped to hear the explanation of the connection between the atom and the molecule, that is, how the magnetic material, in which we may imagine there are atoms with circulating electrons, produces the magnetic moment which he assumes in his current rings. If we could say that a particular grouping of electrons in an atom would give a magnetic effect we should learn a good deal about atomic structure. One of the interesting things that this paper brings out is that possibly the study of permanent magnetism, i.e. the phenomena occurring in magnetic substances, may lead us in that direction. It is very remarkable that the atomic weights of nearly all magnetic substances are approximately equal. The atomic weight of iron, the most strongly magnetic substance, is 56; of nickel is 54 or 55; of cobalt is about 53. With manganese, a steel is obtained which is practically non-magnetic. Manganese has an atomic weight of nearly 55, and possesses the property of preventing magnetic effects in iron, though being quite unable to produce any itself. There are other substances which produce considerable changes in the magnetic quality of iron alloys; for instance, there is silicon, the atomic weight of which is exactly half that of iron. Is there any relation between the atomic weights of substances and the capacity of their atoms to produce magnetism? The whole subject seems to me to be a most fascinating one and one which I hope the physicist, particularly the mathematical physicist, will take up. The author has shown what an extraordinarily small percentage of the two positive and negative forces of the magnet that balance one another remain in the coercive force of the material. In the best magnet steel the value is less than 1 per cent. We have made a number of tests with magnet steels and we have got a maximum figure of about 0·8 per cent. This fact seems to point to enormous possibilities in the improvement of permanent magnets, either by heat treatment or by altering the molecular structure. The heat-treatment method, which, I presume, will alter what the author has called the tribal arrangement in the substance, may produce some effects, but there are greater possibilities in the production of new alloys. That, of course, is borne out by the new cobalt alloy mentioned in the paper, which has a coercive force of over 200. This paper has put the permanent magnet on a scientific basis. The idea that the author has put forward of representing the intensity of magnetization as equivalent to a number of ampere-turns, is extremely valuable as a way of looking at a magnet, and I think that from that point of view alone the paper will be of very great value.

Mr. H. M. Dowsett: The very determined effort which the author has made in this paper to build up a consistent theory of magnetism proceeding step by step from the inter-atomic electron ring to the commercial

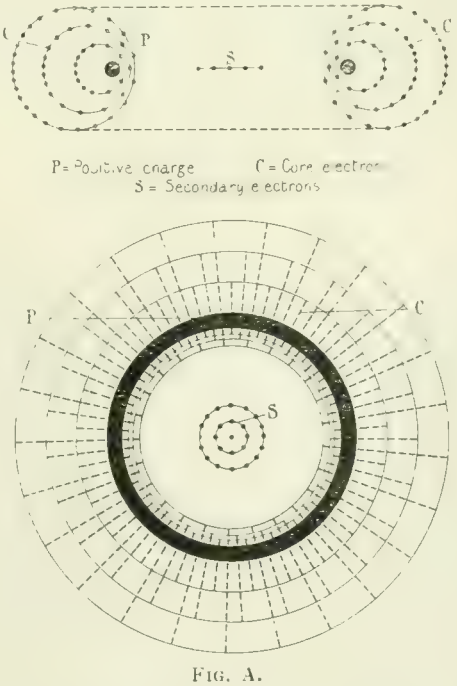


FIG. A.

permanent magnet, will be heartily welcomed by everyone who desires to see physics and engineering practice brought into one consistent scheme of evolutionary development. The weak link in the chain is the character of the inter-atomic electron current, and this of course depends on the structure we postulate for the atom. One cannot mask the fact that models of the atom which are unable to prove their stability when tested by the laws of classical electrodynamics are, in consequence, of little or no use to us in forming a consistent theory of magnetism when theory outside the atom relies entirely on the universal application of such laws. Of the many models suggested to date, the atom of J. W. Nicholson—which consists of a central nucleus and a single ring of electrons in orbital motion round it having vibrations at right angles to the plane of the orbit—is the only one that is electrodynamically stable, and even this model invites a suspicion as to its stability by postulating that its nucleus is split up into many smaller positive charges surrounded by single electron rings. The most extreme case of an electrodynamically unstable atom is the model suggested by G. N. Lewis and developed by I. Langmuir. This consists of concentric shells cut up into cellular spaces, some of which contain electrons, the others being empty. The cells containing the electrons are placed at the corners of a cube, or concentric cubes. In order to endow the atom with magnetism it is necessary to assume that the electrons are rotating rings, and are themselves magnetic. Some years ago I determined to attempt the difficult task of constructing an atomic model which should satisfy the requirements of the physicist and of the chemist and yet should be subject to the gravitational and electrodynamical laws, which, having stood the test of ceaseless application and verification, have been accepted until comparatively recently as being fundamentally true for all natural phenomena. It immediately became apparent that the principal obstacle in the way was the physicist's assumption, as the result of many experiments, that the total number of electrons in the atom could not very much exceed the number representing its relative atomic weight in the periodic series of the elements, and that the positive charge whose constitution and place in the atomic structure we know absolutely nothing about, must therefore be credited with practically the whole mass of the atom. If the whole mass of the atom could be said to be due to the united masses of the electrons—as was at first assumed by J. J. Thomson—and the positive charge and the balance of the electrons above the atomic number could be so arranged in the atom as to be practically insensitive to most means of experimental research, this difficulty would be removed. Proceeding on these lines I devised the model here shown in Figs. A, B and C. In brief it consists, as shown in plan and elevation in Fig. A, of an electron vortex ring, containing one or more shells of high-speed electrons in variable orbital motion round a core of positive electricity, this core being indicated as a continuous thick line in the plan. The speed of the vortex electrons is accelerated as they pass through the aperture of the atom, after which it falls as they return to the outer circumference, with the result that the atom has a translational motion in the same direction as that taken by the electrons nearest to the ring axis. The ring also rotates and thereby produces a magnetic field, and this magnetic field, together with a stray electrostatic field from the positive charge which leaks through the screening of the electron vortex, captures a number of low-speed electrons and causes them to circulate in the aperture

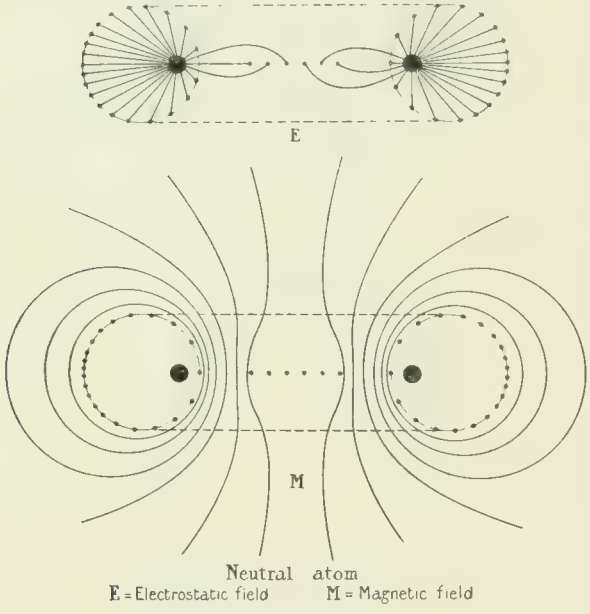


FIG. B.

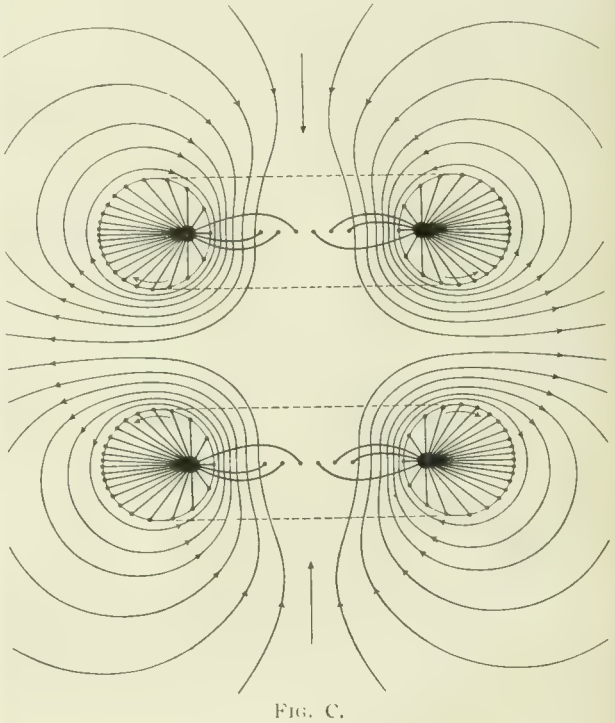


FIG. C.

of the atom in the opposite sense to that of the ring rotation. The number of low-speed electrons captured in this way corresponds to the "atomic number" of the element concerned, and constitutes the source from which the current in a conductor draws its electron supply, and the chemical compound its bonding electrons. Fig. B shows the electrostatic and magnetic fields of a neutral atom of this type, the magnetic wipe-out effect of the secondary electrons being indicated; and Fig. C shows a diamagnetic molecule produced by two identical neutral atoms having the same sense relationship between their vortex and rotational motions, their translational motions, however, their two fields assist each other. Ferro-magnetism is a function of the turning moment which can be exerted on the axis of such a molecule by an extraneous force acting against the inertia of the revolving system, and this is not difficult to calculate; it involves a group relationship such as has been so ably described to us by the author. A discussion of the other reactions of the vortex atom would be out of place on the present occasion, but I have shown elsewhere that this model is able to act electrically, chemically, and radioactively in a manner which can satisfactorily explain experimental results. My present object is to show that it is possible to devise a simple type of

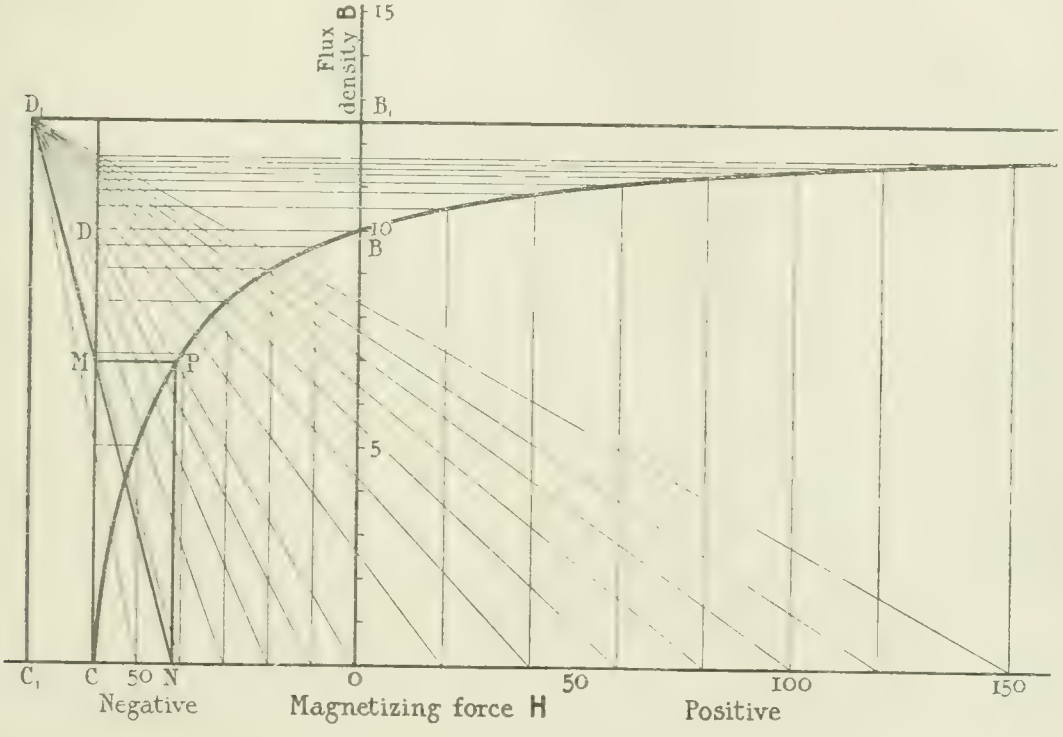


FIG. D.—Graphical construction for B–H curve.

being in opposite directions. If the forces inducing translation are greater than the force of magnetic repulsion, the two atoms will move together in space as one neutral diamagnetic molecule, which according to Langevin is the condition that the molecule always tends to assume. The spectrum lines are due to the accelerations of the vortex electrons. If a very strong magnetic field is applied to a diamagnetic molecule it will react differentially on the rotational speeds of the two atoms, and this will cause differential changes in the electron vortex speeds so that the double line spectrum, or Zeeman effect, is produced. If the magnetic repulsion is greater than the effective force causing translation, then either the molecule will be monatomic and paramagnetic, or it may be diatomic, but the relation between the sense of the vortex motion and the sense of the axial rotation must be different in the two cases, so that when translational forces bring them together atom which conforms to the laws of electro-dynamics, and also affords a reasonable basis for a complete theory of magnetism which can start with the constitutional movement of the electrons in the atom.

Mr. E. A. Watson: The point which interests me most is the importance of the shape of the B H loop for a magnet. In the past it has generally been the custom to define a magnet as having a certain remanence and coercive force, without paying any attention to the shape of the loop. It is quite clear that it is possible to have magnets of the same remanence and coercive force but with loops of a widely different shape and giving very different values for the quantity $\beta\phi$ which determines the performance of the magnet. If it be possible to define a magnet completely in terms of three numbers it is a great advantage. Professor Kennelly pointed out some time ago that for a piece of soft iron the following relation held: $H/B = a + bH$.

A similar equation can, I find, be used to express the relation between H and B for a piece of hard steel, only in this case we must substitute $(H + H_c)$ for H, so that the equation becomes:

$$(H + H_c)/B = a + b\,(H + H_c)$$

The loop for a magnet may thus be expressed in terms of three definite quantities, the coercive force H_c and the two constants a and b. If we inquire more closely into the physical meaning of these constants we find that a is the slope of the curve where it crosses the axis B = O, and that b is equal to $1/B_s$, where B_s is the saturation density of the steel when H is infinite. This relation is in itself of value, as it permits the demagnetizing loop for any steel to be readily laid down and defined, but it also has the advantage of leading to a graphical construction which enables the curve to be very quickly and readily drawn when any three of its characteristic points are given. Fig. D herewith shows the construction in question. It is assumed that the quantities given are: (1) The saturation density B_s, represented by O B_1 in Fig. D; (2) the remanence represented by O B; (3) the coercive force represented by O C. Draw B D and C D perpendicular to one another and meeting in D. Join O D and produce it until it meets a horizontal line through B_1 in D_1. From D_1 draw any series of radiating lines cutting C D and O C, and where they cut these draw perpendiculars to meet each other. The point of intersection of any pair of perpendiculars is a point on the curve determined by the three quantities given, so that the curve can be very quickly drawn. Further it can be shown that the point at which the line O D intersects the curve is the point at which $\beta\phi$ is a maximum. I have applied this construction to a large number of magnet steels and I find the agreement to be within the limits of error over the important portion of the curve, i.e. between the points B and C. In general the value of B_s is not given and, indeed, is not very easily measured, but it can be obtained quite readily by construction when any other single point on the curve beyond the values of B_{rem} and H_c is known. For example, if P is such a point, draw perpendiculars P M and P N to the axis and produce N M to intersect O D, then the point of intersection D_1 must lie on the horizontal line $B_1 D_1$. There is one other question I should like to ask the author; that is, what provision does he make in his machines against momentary excessive armature reaction such as might be caused by a short-circuit? In a machine with an electromagnet such a pulse of excessive current would of course reduce the flux in the magnet temporarily but would have no permanent ill effect, whereas with a permanent magnet an excessive current with its accompanying armature reaction only lasting a fraction of a second will cause a permanent reduction in the field strength, which can only be restored by remagnetizing. This, in my opinion, is one of the chief troubles experienced in practice with generators having permanent magnets, and it would be interesting to learn if the author has found any way of overcoming it.

Mr. A. P. Young: According to the author's theory of magnetization, there are molecular current rings which are free to move so that their magnetic axes tend to line up with the magnetizing field. This is a very beautiful conception, but on this basis I should be interested to have the author's explanation of the fundamental difference in molecular structure that must exist between magnetic and non-magnetic materials. Presumably, the molecular current rings that he has pictured for us must exist in all grades of matter. It has always appeared to me very remarkable and significant that if the two magnetic materials iron and nickel be combined in the proportion of three parts of iron to one part of nickel, the resultant alloy —known as 25 per cent nickel steel—is almost entirely non-magnetic, having a permeability of 1·2 to 1·3. I had considerable experience with this remarkable alloy during the war, and found that it was necessary to keep the nickel content within fairly fine limits, i.e. between 24·5 and 27·5 per cent, to obtain a non-magnetic alloy. Outside these limits, the alloy rapidly exhibited magnetic properties. Another rather curious fact was that, quite frequently, the forgings received from the steel manufacturer were distinctly magnetic, even when the percentage of nickel was correct. In such cases, however, it was always possible to restore the material to the non-magnetic state by simply heating the forgings to 1,000° C. and allowing them to cool slowly in air. I believe if one were to pursue this line of thought in an endeavour to find explanations of the peculiar behaviour of this alloy, it would do much to throw light on the whole phenomena of magnetization. It is interesting to know that the author has been using the maximum value of the product $\beta\phi$ as a criterion of magnetic quality for the past 18 years. The magneto manufacturers, who of necessity have had to study closely the whole subject of permanent magnets in recent years, thought that they had really achieved something a year or so ago when they concluded that this was the best criterion of quality that they could find. This goes to show that after all there is nothing new under the sun. The maximum values of $\beta\phi$ given in the paper for tungsten steel range around 300,000. I think this figure is rather on the high side, because my experience with many thousands of tungsten-steel magneto magnets goes to show that, on the average, the figure is more nearly 250,000. The new cobalt steel, about which one is slowly beginning to glean a certain amount of information, gives a maximum value of $\beta\phi$ of the order of 900,000. One can judge from this what a revolutionary effect the commercial introduction of this new steel would have on all industries which depend in any way for their development on the use of permanent magnets. The question of permanence, as Major Edgcumbe has pointed out, is a very important factor. One has hitherto assumed that, if a magnet is to be reasonably permanent during its life, the coercive force must not fall below a certain minimum which has, as a result of experience, been fixed at 55. It is doubtful, however, whether a large coercive force by itself will ensure that a magnet which is subjected to excessive vibration and extreme cyclic variations in temperature in service (for example a magneto magnet) will remain permanent. One has a

feeling, which is the outcome of one's cumulative experience in this direction, that there is some other factor or factors, not revealed by a magnetic test, which must be taken into consideration. I should like to have the author's views on this particular aspect of the general problem of permanent magnets. In conclusion, I think he is to be congratulated on his epoch-making paper. To my mind its great value to the scientific world will lie, not so much in the facts and theories that it so clearly enunciates, but rather in the stimulus and incentive which it will give to all those who are in any way concerned with problems of permanent magnetism, to pursue the line of thought and investigation initiated by the author.

Dr. E. H. Rayner: The paper raises again a fundamental question concerning the properties of certain kinds of matter, one which is of vital importance to the electrical engineer and of the most absorbing interest to the physicist, namely, the basis of the characteristic of ferro-magnetism. I do not propose to attempt to explain this property of certain forms of matter, but to suggest one or two conceptions which recent developments of physical theory seem to indicate as likely to be of importance. We have, to start with, the modern conception of the atom in which a planetary system of electrons, each possessing a charge of negative electricity, gyrates round a central positive system. The number and, perhaps, arrangement of electrons are directly associated with the atomic weight, and therefore with the characteristics of the atom, and give each element its particular properties. In the general case such a system, if the electronic orbits of a single atom are arranged indefinitely in space, will exhibit no magnetic polarity. In order to exhibit polarity there must be some concentration of the motion of the electrons into one direction such as exists in the solar system, in which the planets all circulate roughly in one plane, or at least on the surface of something like cylinders. An atom, or system of atoms, which possesses such a polarization, will in general have its external field largely neutralized by neighbouring ones, as they will tend to line up so as to produce a closed field. For the mass to exhibit polarity, it would appear necessary that under the influence of an external field, for instance, the motion of the individual electrons in large numbers of atoms must be induced to rotate about axes more or less parallel. It is possible that, in many atoms, there is a particular constraint, associated with the distribution of electronic motion, which prevents an external field from producing the orderliness of motion necessary for the production of magnetic polarization. Bodies composed of such atoms would be non-magnetic. This would also be the case if, in spite of orderliness being part of the nature of the electronic motion in the atom, the constraint were due to the arrangement of the molecular or larger aggregation. There remains the crux of the problem; if this theory of the structure of the atom is approximately correct why is iron almost unique in its properties? The electronic theory of the atom and the development of experiments on the space-lattice structure of matter are what we look to for further speculations on the magnetic theory, and it is to be hoped that our physicists will attack this problem with all the forces at their command. I have only one suggestion to make. The electronic theory differentiates atoms of the various elements largely according to the number of electrons they possess. Now if we have a system of n^3 electrons, or electronic systems, as they may be (the complexity of the spectra of elements argues similar complexity in the electron), it is possible to arrange such a number of electrons in very simple symmetrical systems, which may be illustrated by the corners of a cube, which are 2^3 in number, or by the sides of an octahedron, which are 2^3 in number. A similar symmetry is obtainable with $m \times 2^3$ systems. The atomic weight of iron is about 56, i.e. (7×2^3), and it may be that this peculiar symmetry endows the atom and its agglomerates with the properties of ferro-magnetic bodies. There is also a peculiar symmetry associated with the number 7. For instance, a regular hexagon is formed by one central point and six surrounding it, at equal distances from the centre and from each other. Such a system may be regarded as being composed of six equilateral triangles, and such a plane figure can only be formed by a 7-point type of symmetry. The other elements which exhibit magnetic properties either alone, or when associated with certain other elements, as in the case of manganese in the Heusler alloys, possess atomic weights very close to 56, as Professor Marchant has stated. The four, manganese, iron, nickel and cobalt, have atomic weights between 55 and 59, while there is a relatively large jump to chromium (52) below, and to copper (63) above, both of which are non-magnetic. If we assume, and it is of course a large assumption, that electronic number distribution determines atomic properties, including magnetism, then it would appear that atomic weight, which is associated with electronic number, must govern such things as magnetic properties, and magnetic properties must be the result of something dependent upon number and probably upon a peculiar symmetry associated with number.

Colonel R. E. B. Crompton: I think this is an epoch-making paper, but I am sorry that after all the trouble we have taken in standardizing symbols the author should introduce new ones. The correspondence in which I, as Honorary Secretary of the International Electrotechnical Commission, shall be involved in consequence from all parts of the world will be a serious matter. As no doubt the discussion on this paper will continue for some time, the paper will be discussed in all parts of the world.

Mr. J. D. Morgan (*communicated*): A more favourable time could hardly have been chosen for bringing forward again the subject of permanent magnets, and this paper will have been read with eagerness by many who have been working independently on some of the problems discussed in it. I will limit my remarks to a brief observation on one practical point. The author shows in section (23) how to compute the minimum volume of magnet steel which will produce a particular result. He starts by assuming that a certain energy is required in a given magnetic field and proceeds to calculate how that energy can be most economically provided. I submit that to start off

with the idea of energy in the field brings with it peculiar and unnecessary difficulties. It would appear that the author has had some consciousness of this, from the fact that he has devised arbitrary units to avoid the quantity 8π which necessarily occurs in the energy equation. To me it seems easier to state the problem thus: A given flux is required in a given air-gap. Show how the least volume of magnet steel is to be found. The attack is commenced by putting down the familiar equation

$$N = M/\rho \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where N = flux required;
M = magnetomotive force;
ρ = reluctance.

Obviously (1) is not in a form which gives much help, and it must be transformed by multiplying both sides by $N\rho$, giving

$$N^2\rho = N \,.\, M = BA \,.\, HL = BH \,.\, AL \quad . \quad (2)$$

where B and H have the usual significance, and A and L denote area and length of magnet respectively. $N^2\rho$ contains the condition of the problem. B, H, are correlated on the demagnetization curve; and A, L, are connected with the answer to be sought. When the product BH is a maximum, the product AL is a minimum. This argument leads to the same result as that given by the author, but it seems to keep the essential factors N and ρ more directly in view than one which merges them in an equation of energy.

Mr. W. Phillips (*communicated*): All users and makers of permanent magnets owe the author a debt of gratitude in establishing a practical working theory of permanent magnets. Up to the present their design has been more or less a rule of thumb matter. There is one point upon which I should like to be enlightened. It is the common experience of makers of permanent magnets that very often the best are cracked. These cracks may run longitudinally, or at times directly or partially across the section. It seems to me that the presence of the cracks may somewhat modify the theory of the internal arrangment, and I should be glad to learn what modification, if any, is necessary to account for the usual high strength of the magnet despite the presence of these defects.

Mr. E. B. Wedmore (*communicated*): Whilst the author promises further contributions on the practical application of his theories, I hope we may yet have also some further contributions on the theoretical side. The diagrams in the early part of the paper serve the author's immediate purpose, but before progress can be made something more elaborate will be necessary. We are dealing with a problem in three dimensions (for the moment leaving out Einstein and the fourth dimension), and diagrams in two dimensions will not take us far. We are accustomed to such diagrams in works on chemistry, but they are not very convincing. Whatever the simplest arrangement of the rings may be in non-magnetized iron, it must be, in the mass as a whole, a symmetrical one in three dimensions and cannot therefore be a simple extension of that shown in the diagrams, as will be seen at once if we endeavour to place corresponding arrows on the 12 edges of a cube. A study of three-dimensional space-lattices shows that there are remarkably few possible symmetrical arrangements. Suppose we take a large non-magnetized crystal of a paramagnetic material, we have grounds for believing (see, for example, the works of Professor Bragg) that we have a body in which the atoms are grouped according to one of the known space-lattices, and the axes of the rings are grouped to satisfy the condition of no external field. If the atoms now absorb each others' fields by the formation of interlinking loops also on a space-lattice pattern both homogeneous and symmetrical throughout, then when the material is magnetized in any direction we shall have a breaking down of an arrangement symmetrical in three dimensions into one symmetrical in two dimensions only. This involves a much more drastic change than is shown by a two-dimensional diagram, and until we have a complete description of what occurs I find it difficult to believe that there would not be a passage through one or more intermediate stages of partial polarization, involving steps from one configuration to another. It may be possible to secure large enough crystals of iron or a group large enough and symmetrically placed to test this. In iron as we know it, in the bulk the irregularities of structure would cause sufficient irregularities in the process of breakdown to cover up any steps which might be involved in the integral portions. It may be, however, that the absence of magnetic polarity in a crystal of iron may be due to the internal structure of the individual atom. On a priori grounds this seems to offer a better chance of fitting in with the existence of magnetizable and non-magnetizable materials, for if the simple ring construction illustrated corresponds to the facts, why is it that we cannot highly magnetize materials having atoms in which there are just a few electrons around the nucleus? If it is because of some neutralization by magnetic interlocking, how can this exist in the gaseous state when the atoms are freely travelling? And if not in this state, we could magnetize the gas and then cool it in a magnetic field and so get a magnetized solid. But enough of speculation; we want some crucial experiments, and I suggest that possibly the examination of crystals may bring out some new facts. I would ask whether crystals show homogeneous permeability or axial, and whether the breakdown is in steps.

Mr. S. Evershed (*in reply, communicated*): I need not say how very much I appreciate the cordial way in which the paper has been received. The value of a paper of this kind, speculative as it must be on the theoretical side, was very well put by Mr. Young, and I can truly say that in preparing it my aim has been not so much to propound new theories as to stimulate thought by restating Ampère's and Ewing's theories in the light of modern knowledge of the electronic constitution of the atom. The discussion has covered a wide field, and naturally enough it has been directed for the most part to the formidable difficulties which confront the physicist when he attempts to build up an atom out of electrons and endow it with all the fundamental properties—chemical, electric and magnetic,

together with a multiplicity of modes of vibration—which are characteristic of the real atom.

In basing the paper on Ampère's hypothesis I have taken for granted the presence of electrons travelling in molecular circuits, and have assumed their orbits and their speed to be such as will give the iron molecule the magnetic moment which, from experiment, it is known to possess. I have not ventured to penetrate the mystery of the atom, with its positive nucleus and highly complicated system of electron orbits. Remembering that in Ewing's model, which faithfully reproduces the cyclic curve of magnetization, the magnetic elements are little compass needles of demonstrably constant magnetic moment, I feel justified in attributing the same constancy to the iron molecules with their electronic currents, and for the purpose of the paper I regard magnetic molecules as so many current rings carrying constant currents and behaving like a Ewing model made up of a lot of little moving coils connected to a battery, or other source of energy.

At this point Mr. Atkinson dissents from my view, saying in effect that in the case of the molecular circuits there is no battery and no source of energy corresponding to it; nothing to keep the molecular current constant. Now I do not suppose that Mr. Atkinson and I are at variance in our ideas about energy, and the need for an available store of it if the molecules are to behave as I believe they do; but perhaps we have neither of us succeeded in making a completely satisfactory statement of the problem. When I wrote that on passing from the unstable to the stable state, the energy of a mass of magnetic molecules increases, I was thinking not of the total energy of the system but solely of that part of it with which we are more immediately concerned in dealing with permament magnets, the magnetic energy associated with the mutual induction of the molecular circuits, and I ought to have made that clear. The question whether the molecular current really is constant or not is an old controversy, and I certainly thought it had been finally disposed of by Langevin. No one would think of traversing Maxwell's conclusion that a current in a circuit of no resistance cannot remain constant under electromagnetic induction unless there is an electromotive force, or some other source of energy, to maintain it. We are surely all agreed about that so far as the principle is concerned, and I imagine that the difference between Mr. Atkinson's view and my own really turns, not on the fact that changes in current strength take place, but on the magnitude of those changes. Mr. Atkinson tells us that the changes in the molecular current "must be very great"; Langevin, as I understand him, proves them to be quite negligibly small. So small indeed as to be quite beyond experimental detection with any magnetic fields we can produce at present; although if we should ever be able to apply fields of several million gauss there would probably be another story to tell.

But quite apart from Maxwell, who was unacquainted with electrons, and Langevin who, knowing about electrons, was mainly concerned with the explanation of diamagnetism, it seems to me that the question of the magnitude of the current change in the electronic molecule, when electromagnetic changes occur, is one for a little wholesome arithmetic. Let me state the problem in my own way and bring it to the test of arithmetic if I can. Take the simple case dealt with by Maxwell;* but instead of ascertaining, as he did, the action of a magnetic field produced by a circuit of any kind on a molecular circuit of no resistance, let us suppose the field-producing circuit is itself a molecular circuit, so that we have two identical circuits of no resistance, each having an area s and carrying a current which in the initial state of things may be denoted by i_1. Then if m is the mass of an electron, v_1 the initial velocity of the electrons, e the electron charge, and x the number of electrons in each circuit, the energy in the system of two circuits when in relative positions of zero mutual induction will be:

$$m x v_1^2 + \mathrm{L} i_1^2 ;$$

L being the self-inductance of each circuit. In this state each circuit applies a torque to the other, equal to $i_1^2 d\mathrm{M}/d\theta$, and they therefore move round on their pivotal axes in a direction which increases their mutual induction. Their rotation will continue until the mutual induction reaches a maximum value M, and ultimately they will come to rest in this position, their energy of rotational or deflectional motion having been dissipated as heat. Denoting this wasted energy by W, and indicating the final electron velocity and current by v_2 and i_2 respectively, then, provided no energy is given to the system, the energy equation between the initial and final states will be:

$$m x v_1^2 + \mathrm{L} i_1^2 - \mathrm{W} = m x v_2^2 + \mathrm{L} i_2^2 + \mathrm{M} i_2^2 \quad . \quad (37)$$

If the molecular orbits were like ordinary electric circuits, the wasted energy W would be equal to the increment in the energy of mutual induction, namely $\mathrm{M} i_2^2$. But for the present purpose it is not necessary to assume that equality, and provisionally we may put $\mathrm{W} = k\mathrm{M} i_2^2$. Here k is a constant which would be zero if it were possible for the relative movement of the two molecules, from the initial to the final state, to take place without any waste of energy. But the constant cannot in any case exceed unity, and it will be seen, presently, that the question at issue does not depend on the precise value which k may have.

If r is the radius of the molecular circuit and n the number of revolutions per second which the electrons make round their orbits, then $v = 2\pi r n$, and, remembering that $i = e n x$, we shall have $v_1^2 = \left(\frac{2\pi r^2}{e x}\right) i_1^2$ and $v_2^2 = \left(\frac{2\pi r}{e x}\right)^2 i_2^2$. Substituting these values in equation (37) and putting $\pi r^2 = s$, then:—

$$i_2^2 = i_1^2 \left\{ 1 - \frac{(1 + k)\,\mathrm{M}}{4\pi s \frac{m x}{e^2 x^2} + \mathrm{L}} \right\} \quad . \quad . \quad (38)$$

Now although numerical values for some of the quantities in this equation are at best conjectural,

* "Electricity and Magnetism," vol. 2, art. 836.

yet if the two circuits are regarded as two adjacent molecules placed at a distance of about $3/10^8$ cm. between their centres, and if any reasonably possible values are assigned to the other quantities, then the magnitude of the fraction, which represents the decrement of the square of the current, will be found to be quite negligible compared with unity. For example, if we take the accepted figure for the mass of the electron as $8\cdot8/10^{28}$ gramme, and suppose the other quantities to have the values I have given for them in the paper, then L will be found to be of the order $1\cdot7/10^7$ C.G.S. magnetic units; and for two molecules of iron, each containing 56 electrons, the magnitude of the fraction will be $(1 + k) \times 0\cdot7/1{,}000{,}000$.

To err in the direction which over-estimates the decrement of current, we can suppose k to have its maximum possible value, namely, unity, which will give the fraction its greatest value, namely:

$$2\,\mathrm{M}\Big/\left(4\pi s\,\frac{m\,x}{e^2\,x^2} + \mathrm{L}\right)$$

or in the arithmetical example $2 \times 0\cdot7/10^6$. Remembering that the square root of the difference between unity and any very small fraction is equal to the difference between unity and half the fraction, equation (38) now reduces to

$$i_2 = i_1\left\{1 - \frac{\mathrm{M}}{4\pi s\,\dfrac{m\,x}{e^2\,x^2} + \mathrm{L}}\right\}\text{*} \quad . \quad . \quad (39)$$

and, with the values taken by way of example, this equation becomes:

$$\text{Final current} = \text{initial current} \times \left(1 - \frac{0\cdot7}{1{,}000{,}000}\right)$$

It should now be noticed that if $k = 0$ is a possible condition, then the value of the fraction, or in other words the decrement of current, would be half the amount given in the above equation.

So far, then, my arithmetic confirms the conclusion arrived at by Langevin, that the change in the molecular current which results from electromagnetic induction is negligibly small, for it appears that when two electronic magnetic molecules, placed at a molecular distance apart, rotate on their pivotal axes so as to increase their mutual induction from zero to the maximum value which it can have for the given distance, then the current in each molecule decreases by less than one-millionth part. Hence the two molecules are able to behave as though they were coils connected to a battery, for they contain in themselves the needful store of energy, and, so far as permanent magnets are concerned, the laws of interaction between ordinary electric circuits, laws with which we are all familiar, may be applied to magnetic molecules without sensible error.

Maxwell foresaw the possibility that electricity might possess mass or some property equivalent to mass, but in treating of the induction between circuits of no resistance he took no account of it. Suppose we, too, leave the mass of the electrons out of account by putting $m = 0$, so that the first term in the denominator of the fraction in equation (39) vanishes. The equation for initial and final currents in each of the two molecular circuits then becomes simply

$$i_2 = i_1\left(1 - \frac{\mathrm{M}}{\mathrm{L}}\right) = i_1\left(1 - \frac{\mathrm{M}\,i_2}{\mathrm{L}\,i_2}\right) = i_1\left(1 - \frac{\mathrm{H}\,s}{\mathrm{L}\,i_2}\right) \ldots (40)$$

which is Maxwell's equation for the case of a circuit producing a field H acting on a molecular circuit of area s in which the initial current is i_1 and the final current i_2.

It is interesting to note that Maxwell, with unerring finger, pointed to the fraction $\mathrm{H}s/\mathrm{L}i_2$ as containing the answer to the question whether Weber's theory of magnetization—which assumed constant magnetic moment, constant molecular current on Ampère's hypothesis—was well founded or the reverse. He clearly foresaw the time when the magnitude of the fraction would become known and the question as to the degree of constancy in the molecular current would be answered, and he pointed out that the value of the fraction depended in part on the proportion between the radius of the molecular circuit and that of the section of the channel in which the molecular current flowed.* But he makes no reference to the effect which the mass of the electricity (if it should be found to possess any such property) would have in diminishing the magnitude of $\mathrm{H}s/\mathrm{L}i_2$. Nor does Maxwell refer to what, in the absence of mass, is necessarily the principal factor in determining that magnitude; namely, the proportion between the radius r of the molecular circuit and the distance d between adjacent molecules. Yet, as I shall now show, when the case of two identical molecules is taken, so that $\mathrm{H}s/\mathrm{L}i_2$ becomes simply M/L, we have only to express M and L in terms of molecular dimensions to arrive at once at the principal factor in the ratio M/L. For two identical circuits of small size compared with their distance apart:—

$$\mathrm{M} = 2\,s^2/d^3 = 2\pi^2 r^4/d^3.$$

For a circular circuit $\mathrm{L} = 4\pi r \log(1\cdot39\,r/a)$, where a stands for the radius of section of the conductor, or, as Maxwell calls it, the channel, in which the current flows. Hence $\mathrm{M/L} = 2\pi^2 r^4/4\pi r\,d^3 \log(1\cdot39\,r/a)$, or

$$\frac{\mathrm{M}}{\mathrm{L}} = \frac{\pi}{2\log(1\cdot39\,r/a)} \cdot \frac{r^3}{d^3} \quad . \quad . \quad . \quad . \quad (40)$$

The electrons running round a molecular orbit cannot be said to be moving in a well-defined channel of measurable transverse dimensions, nevertheless it is possible to make a reasonable guess at the radius of an *equivalent section* of channel so to speak. And it should be noticed that we might extend our choice for the size of channel over very wide limits without affecting the value of $\log(1\cdot39\,r/a)$ so far as its order of magnitude is concerned. An example or two will make this clear. I imagine the size of an electron is a somewhat elusive quantity, but to err on the safe side—that is to say in such a direction as

* Mr. Atkinson has referred to the expansion or contraction of the electron orbits which probably takes place concurrently with changes in the speed of the electrons. It should be noticed that any alteration in the orbit areas which may come about in this way must be an *expansion* when the speed *falls*, and vice versa; hence by treating s as constant, in arriving at equation (39), the magnitude of the decrement of current is, if anything, over-estimated.

* *Loc. cit.*, vol. 2, art. 844.

will make M/L too large rather than too small—I shall assume the radius of an electron to be $1 \cdot 8/10^{13}$ cm.; that being a figure given by Dr. Crehore,* and the largest estimate I have come across. As regards the radius of orbit, I shall adhere to the value I assumed in the paper, namely $r = 1 \cdot 5/10^{9}$ cm., which gives the orbit a diameter equal to one-tenth of the distance between centres of molecules. I set no store by this particular proportion of orbit to molecular distance, but it seems obvious that if the electrons are to perform their revolutions round the orbit without suffering violent perturbations from the action of neighbouring molecules r must be very much less than d. Now suppose the cross-section of the equivalent channel has a radius equal to that of the electron—and it cannot very well be less than that—then we shall find $\log (1 \cdot 39 r/a) = 9 \cdot 4$. Or if we make the channel 10 times that size then $\log (1 \cdot 39 r/a) = 7 \cdot 1$, or if it is 100 times the radius of the electron, then $\log (1 \cdot 39 r/a) = 4 \cdot 8$. From these numerical examples it is clear that the ratio r/a, which was the only factor considered by Maxwell, is of relatively small importance, and the dominant factor in the fraction M/L is the ratio r^3/d^3. Hence, in view of the reason I have just refererd to for believing r to be necessarily ever so much less than d, the ratio r^3/d^3 must in any case be a very small fraction, and whatever value we may choose for r/a—within reasonably probable limits of course—the ratio M/L will be found to be quite negligible compared with unity. In other words, the final molecular current will not be sensibly less than the initial current. If, for example, we assume the radius of the equivalent channel to be 10 times the radius of an electron, that is to say if we put $a = 18/10^{13}$ and as before make $r = d/20$, then we shall have $\log (1 \cdot 39 r/a) = 7 \cdot 1$ and

$$\frac{M}{L} = \frac{\pi}{2 \times 7 \cdot 1} \left(\frac{1}{20}\right)^3 = \frac{28}{1{,}000{,}000}$$

The equation for the final molecular current then becomes :

$$\text{Final current} = \text{initial current} \times \left(1 - \frac{28}{1{,}000{,}000}\right).$$

Hence, even on the supposition that the only energy stored in the system is that associated with self induction, the decrease in molecular current resulting from rotational movements which change the mutual induction from zero to maximum is quite negligible in amount.

So much for the action of one molecule on another. To determine the action of an extraneously applied magnetic field on the current in a molecule, our fraction must be stated in the form Hs/Li_2, and here again a little arithmetic will develop a useful sense of proportion. For example, if we wish to find what strength of field will diminish the molecular current by 1 per cent, we must put $Hs/Li_2 = 1/100$, or $H = Li_2/100s$. Then, leaving the mass of the electrons out of account and taking the same molecular constants and dimensions as before, it will be found that H must be no less than 1,500,000. Obviously then, for any fields we are able to apply in practice, the fraction Hs/Li_2 will be negligibly small compared with unity, and there will consequently be no sensible change in the molecular current.

To sum up the whole matter, the test of arithmetic shows, I think, conclusively, that in the fraction Hs/Li_2 or Mi_2/Li_2 or, in other words, the ratio of the induced flux to the self-created flux threading a molecular circuit, the numerator is always negligibly small compared with the denominator; the latter representing the relatively vast store of magnetic energy contained in the magnetic molecule. It is this enormous disparity between induced flux and the self-created flux which, quite apart from the mass of the electrons, justifies the assumption made in the paper, namely, that in dealing with the ordinary effects of permanent magnetism Ampère's molecular current may be regarded as constant. And with a molecule of all but perfectly constant magnetic moment, theory comes into line with the only experimental evidence we possess, namely that afforded by the Ewing model with its elements of constant magnetic moment, and the fact that the strongest magnetic fields so far attainable have failed to bring about any detectable diminution in the maximum intensity of magnetization in iron.

For my part, then, I accept the molecule of practically constant magnetic moment, and I do so the more readily because it provides the necessary foundation for Ewing's explanation of the cyclic magnetization curve. It is of course open to Mr. Atkinson or to anyone else, starting from another base, to explain that highly complicated curve in some other way; but so far no other rational explanation has been forthcoming, and Ewing's theory, founded on the molecule of constant magnetic moment, holds the field.

I need not refer at any length to the experiment with a magnet and soft iron keeper carried out some 30 years ago by the late Dr. S. P. Thompson* and adduced by Mr. Atkinson in support of his argument. The magnitude of the flux-changes which take place at the neutral section of a permanent magnet when a soft iron keeper is applied or removed depends on the proportion which the reluctance of the air path, the path short-circuited by the keeper, bears to the whole reluctance of the magnetic circuit, and in all cases the reluctance of the path inside the magnet itself forms by far the greater portion of the whole. In any ordinary bent magnet in which the two limbs are parallel, so that the end faces are at some considerable distance apart, putting on a keeper or pulling it off makes a flux change round about 10 per cent at the neutral section. If a magnet is shaped so that its ends are brought closer together, the reluctance of the air path is considerably diminished, and the flux change can readily be reduced in that way to 3 per cent or less. In the old-fashioned horse-shoe magnet, with which we were familiar in our youth, the ends are so close together that the reluctance of the air path between the end faces becomes almost negligibly small compared with that of the magnet. Hence, in a magnet of that type the flux change at the centre when the keeper is put on or taken off is reduced to a very small amount, and it would

* *Philosophical Magazine*, 1913, vol. 26, p. 56.

* For a description of the experiment, see "The Electromagnet," by S. P. Thompson, pp. 211–213.

not be surprising to find that it had escaped detection with the testing apparatus employed in the early days. Obviously, if the end faces were brought so close together as to come into contact, there would no longer be any air path to short-circuit, and hence in the limit the flux change resulting from the application of a keeper must necessarily fall to zero.*

Major Edgcumbe and other speakers referred to the question of stability in the magnetization of permanent magnets. This is, of course, a vital matter for the instrument maker and even more vital for those who depend on permanent magnets in supply meters. I have not touched on stability, however, because the subject more properly belongs to the manufacture of magnets than to their predetermination. The same remark applies to the subject of cracks in hardening which was mentioned by Mr. Phillips. I hope on another occasion to deal with both these important matters.

Major Edgcumbe is quite right when he says that where a magnet is subjected, in ordinary use, to powerful demagnetizing forces, the economic density in the steel is not the sole factor to be taken into account in design. In all such cases economy of steel can only be secured by eliminating the demagnetizing forces, or by neutralizing them if actual elimination is impracticable. The ordinary ignition magneto is a peculiarly unfavourable example and, so long as no successful attempt is made to eliminate excessive armature reaction, the magnets must necessarily weigh two or three times as much as an economic magnet.

Dr. Marchant drew our attention to the curious fact that the three so-called ferro-magnetic elements all have about the same atomic weight. This is unlikely to be a mere coincidence, and yet, seeing that the atomic weight of the non-magnetic element manganese comes nearer to that of iron than either nickel or cobalt, we are left wondering what it all means. If anyone should succeed in converting a non-magnetic into a magnetic element I hope it will be one of higher atomic weight than iron and therefore containing more electrons. For only in this case could it yield an equivalent current of more than 17,000 amperes per cm. and be an improvement on iron.

I heartily concur with Mr. Dowsett when he urges physicists not lightly to abandon well-tried laws every time they find a difficulty in explaining natural phenomena. But, as I have remarked in the paper, the problem of the electronic atom is one of extraordinary difficulty and it may well prove incapable of solution until additional laws, at present unrecognized, have been discovered and co-ordinated with those we already know. My scanty knowledge does not permit me to comment either on Mr. Dowsett's model atom or on Dr. Rayner's interesting suggestions with regard to the general behaviour of electron orbits in a mass of molecules, and the effect of symmetry on the magnetic properties of the mass. Dr. Rayner spoke in very general terms, but he appeared to suggest that he had in mind some alternative to Ewing's explanation of the magnetization curve.

Mr. Watson showed us a very ingenious geometrical construction, founded on Kennelly's formula, by which he is able to set out the demagnetization curve when three pairs of co-ordinates are known. To determine the three co-ordinate points it is of course necessary to provide all the appliances for magnetic testing, and for my part when I had observed those three cardinal points I think I should always prefer to go on and observe half a dozen more, so that the curve might be drawn entirely from experiment. The Kennelly formula appears to agree reasonably well with the magnetization and demagnetization curves, an agreement which suggests that an attempt should be made either to correlate the formula with Ewing's theory of the molecular interactions which give rise to the cyclic curve, or to demonstrate that the formula points to some alternative and perhaps simpler explanation of the actions which are summed up for us in the cyclic curve.

Mr. Young asks for an explanation of the fundamental difference between magnetic and non-magnetic materials. I wish I knew the answer, but, alas, I am continually asking the same question myself. I suppose there can be no doubt about the general principle, however. In a non-magnetic molecule there must be at least two orbits with the electrons running round them in opposite directions so that the magnetic moment of the molecule as a whole is zero. Langevin has shown that a material composed of such molecules is necessarily diamagnetic. In a magnetic material we may suppose that the electrons in the molecules all revolve round their orbits in the same direction, or at all events that there is a preponderance in the same direction. In the paper I have assumed that, in highly magnetic elements like iron, all the electrons present in the molecule are revolving in one direction.

But if the principle is within our grasp, the same cannot be said of the details of the molecular machinery. Iron, as we all know, when at temperatures round about the recalescence point becomes non-magnetic or magnetic as we raise or lower the temperature over a small range, and at any temperature within that range iron is either magnetic or non-magnetic according to whether the particular temperature was reached from below or above. Who knows what are the atomic or molecular rearrangements which apparently cause some of the electron orbits to turn right-about-face, and so convert what had been magnetic molecules into the non-magnetic or diamagnetic type? That such fundamental rearrangements should be possible is perhaps not so difficult

* As carried out by Thompson, or rather by his students, the magnet and keeper experiment appeared to show that when the keeper was applied or removed there was no flux change at all at the centre or neutral section of the magnet; or, as Thompson puts it, the change at the centre was certainly less than one 3,000th part of the flux change at the ends of the magnet. Believing his experiment to be correct, he came to the conclusion that no change could be effected in the total flux in a permanent magnet by putting on or taking off the keeper.

It seemed worth while to refute this, or—if miracles can happen—to confirm it, and Dr. Eccles very kindly sent me the identical magnet used by Thompson in order that I might repeat his experiment. The magnet is a very large one of the old horse-shoe pattern, with its ends very close together. It is of great length, namely 108 cm., and is, in fact, by far the longest magnet I have ever come across. With such unusual proportions we might reasonably expect the flux change to be exceptionally small. On applying or removing the keeper I found a marked flux change at the centre, amounting to 1 per cent of the flux change at each end of the magnet. In other words, the ratio (change at centre)/(change at end) instead of being zero or at any rate less than 1/3,000, as Thompson believed, is actually about 30/3,000. The change is smaller than in any other magnet I have tested, and bears out what I have just said about the abnormal proportions of the magnet. But, small as the flux change has proved to be in Thompson's magnet, it could not possibly be overlooked, and was quite easily measured with accuracy. One can only explain Thompson's negative and misleading result by some unnoticed mishap in conducting his experiment; possibly an accidental break in the circuit of his search coil and galvanometer.

to understand when they occur (as they do in iron) at a high temperature, because at high temperatures we believe the atoms to be vibrating in a violent fashion, which gives them freedom to perform evolutions that would be impossible if they were at rest. But what are we to think when the same changes are found to occur at a very low temperature, as they do in the nickel steel which Mr. Young mentioned? When this steel has cooled down in the ordinary course of manufacture from a high temperature to ordinary temperatures, it is found to be all but non-magnetic; electron orbits back-to-back as it were. But as Hopkinson showed, if this steel (containing 25 per cent of nickel) is cooled down to a temperature some 50° C. or so below zero, it becomes very strongly magnetic and thereafter remains in that state at ordinary temperatures. To re-create the non-magnetic molecular arrangement the steel must be raised temporarily to about 600° C., after which it will remain in a non-magnetic state at ordinary temperatures. Here, then, is a material in which the electron orbits are not only free to turn right-about-face, or perform some equivalent evolution, at a high temperature, but can perform the same thing the other way round at a temperature below zero; so low a temperature, indeed, that one would imagine the atomic heat vibrations to be too feeble to give any effective assistance in bringing about those extraordinary re-arrangements which must take place when the steel changes from the non-magnetic to the magnetic state; a change which is equivalent to the electron orbits in each molecule suddenly quitting their back-to-back positions and turning round until they all face one way, so that the electrons all revolve round their orbits in the same direction. Again we are left wondering what it all means. The metallurgist murmurs the magic word *allotropy*—but we are none the wiser.

Mr. Morgan is inclined to think that I have introduced unnecessary difficulties by stating the magnetic requirement in terms of energy, the product of flux into potential difference. I notice, however, that when he himself proceeds to set down the requirement he states it as the product of the square of the flux into the reluctance, which is of course the energy expressed in another way. I do not follow the steps by which he identifies what I have called the surplus magnetomotive force of the magnet steel with H on the demagnetizing curve. He seems to jump to the conclusion that these two quantities are identical in magnitude, whereas I have gone perhaps a long way round to prove that they are so. Now that I have set up a signpost no doubt a shorter route than mine will be discovered, but I can assure Mr. Morgan that a satisfactory proof of the numerical equality of H and ϕ was by no means easy to find.

As to the units by which magnetic energy is measured, they are none of my making and I must disclaim all responsibility for them. But, after all, I do not think it very much matters whether we measure beans by the peck or by the bushel so long as we have enough of them and they really are beans.

Mr. Wedmore quite rightly draws attention to the very limited number of symmetrical molecular distributions which are possible, and he infers that the magnetization or orientation of a single crystal, built up according to any one of the possible arrangements, would prove to be discontinuous. Much would depend, I think, on the size of the crystal. I feel sure that if it were large enough to give a measurable flux the magnetization curve would be of the normal type free from discontinuity, and I derive my belief from inspection of the cyclic curve given by a model* containing no more than 24 elements, representing that number of magnetic molecules. Although the test-points on the curve show some discrepancies, the curve as a whole certainly suggests that to produce any marked discontinuity it would be necessary to obtain a cyclic curve from a single crystal containing less than 24 molecules and therefore of ultra-microscopic dimensions. For this reason, while I think experiments with large crystals would teach us something useful, I doubt very much if they would elucidate the particular points Mr. Wedmore has in mind.

I agree with Mr. Wedmore that two-dimensional diagrams leave something to be desired. That some-

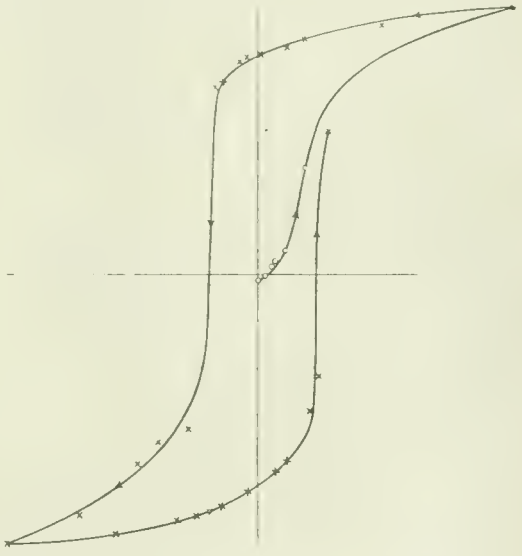


FIG. 159.—Cyclic process of magnetization applied to a group of 24 pivoted magnets. [EWING.]

thing, as it seems to me, is imagination; the capacity to think in three dimensions (or more) while gazing at a diagram in two dimensions. Mr. Wedmore mentions the sort of diagrams one sees in chemistry books, and I recall that perhaps the earliest chemical diagrams were Dalton's quaint drawings of atoms bristling with what I imagine to be bonds of chemical affinity.† Absurd as they were, those drawings did something for chemistry, because by their aid Dalton compelled chemists to think. My diagrams are equally absurd; and my current rings too, when one thinks of the frightful complexity of the electronic atom. Yet, as aids to thought, spurs to the imagination, they will serve a useful purpose if they enable others besides myself to form a mental picture, however dim, of what is going on inside a permanent magnet.

* J. A. EWING: "Magnetic Induction in Iron and Other Metals," p. 338, Fig. 159 (reproduced by the courtesy of the publishers, Messrs. Benn Brothers).

† DALTON: "New System of Chemical Philosophy," 1810, part 2.

ELECTRIC RAILWAY CONTACT SYSTEMS.

By Sir PHILIP DAWSON, Member.

(*Paper received* 10 *June, and read before* THE INSTITUTION, 30 *June*, 1920.)

INTRODUCTORY.

I have been requested by the Council to read a paper dealing with the contact systems used on electric railways from which the current to feed the trains is collected.

There are two distinct types, the older and the one most generally in use in this country being the conductor or live rail, which is only in use with direct current, at pressures varying from 500 to 1,300 volts, though it is proposed to increase the pressure with this system up to 1,500 volts. A conductor rail with a pressure of 2,500 volts has been tried in the United States but has been abandoned, and so far there are no contact rails working anywhere at a pressure over 1,500 volts.

The general details of conductor rail construction are well known and will only be briefly dealt with at the close of this paper.

Where pressures of 3,000 volts, D.C., or 6,000 to 16,000 volts, A.C., or 3,000 to 5,000 volts three-phase are concerned, the questions of safety and of insulation have made it imperative to use overhead conductors. There is one case in this country where an overhead conductor is used with a pressure of 1,500 volts, D.C. The overhead conductor has been used here in order to clear the tracks and yards of live conductor rails.

It is not proposed to discuss the actual question of traction systems in this paper; suffice to say that so far only three countries have decided to standardize any one system for general railway electrification. These countries are Sweden, Switzerland and Germany, who have definitely adopted the single-phase 16,000-volt $16\frac{2}{3}$-period system with an overhead conductor. France is at the present moment investigating the matter, and it appears probable that if they arrive at any definite conclusion, they will adopt the 3,000-volt D.C. overhead system, thus standardizing the voltage as well as the system.

Italy has so far not arrived at any definite conclusion, although the majority of their railways so far electrified are on the three-phase, 16-period, 3,000-volt system. The United States has no definite standard although the Pennsylvania Railroad appears to have decided on the single-phase system for all future electrifications.

The following are the figures regarding the principal electrifications carried out in the United States:—

The New York Central and Hudson River Railroad electrified in 1906, with a 600-volt under-running protected third rail. The mileage of single track electrified to-day is 258.

The Pennsylvania Railroad electrified from 1905 to 1910 the West Jersey and Seashore, the Long Island and the Pennsylvania terminal with 600-volt D.C. third rail, the total mileage being 466.

The New York, New Haven and Hartford Railroad electrified at 11,000 volts single-phase, 25 periods, in 1907, 582 miles of single track.

The Pennsylvania Railroad electrified its suburban system in Philadelphia and the Norfolk and Western in 1913 on the single-phase system, 25 periods, at 11,000 volts, and the mileage electrified on this system is now 201, and their extension on the Great Horseshoe Bend is going to be on the same system.

The Milwaukee, St. Paul and Puget Sound Railroad electrified in 1913 on the 3,000-volt overhead D.C. system.

This railroad is mainly a single-track mountain railway using locomotives, and there are so far 647 miles of track electrified.

In this country the whole question is under examination as to how far any one system shall be adopted as a standard for general railway operation.

Dealing with overhead construction for railways in a country where traffics are very intense and the hours of service long, the overhead construction has to be a very different thing from what has been so satisfactorily adopted for electric tramways. In this case it is obvious that the overhead construction must present factors of security and safety at least equal to those obtaining on the permanent way, and it must be constructed in such a way as to enable any maintenance and supervision to be carried out in the very limited periods of time available for such purposes.

An overhead conductor can only be utilized where the currents to be collected from it are relatively small, as experience has shown that heavy currents are not only difficult to collect, but also very greatly increase the cost of maintenance.

OVERHEAD CONDUCTORS.

(A) GENERAL PRINCIPLES.

The overhead construction and the collector arrangements on the coaches or locomotives must be such as to make it certain that the collector bow will never be liable to come off the contact wire, and must also follow the contact wire with the utmost flexibility, and for this reason the ordinary trolley-wire construction utilized for tramway purposes is obviously unsuitable: in other words, the risk of a collector coming off the contact wire must be no greater than the risk existing to-day of the wheels of a bogie coming off the track.

The overhead construction must be designed and put up in such a manner that, whilst minimizing the risk of failures, the cost of maintenance and the time required for renewal or replacements of any individual portion requiring attention should be reduced to a minimum; at the same time the capital cost must be kept as low as possible.

alterations have had to be carried out both in the United States and in Germany, the principles adopted in connection with the overhead construction on the Brighton Railway were such that the overhead construction in operation to-day is practically identical with that originally designed.

The Germans adopted in the case of the Hamburg

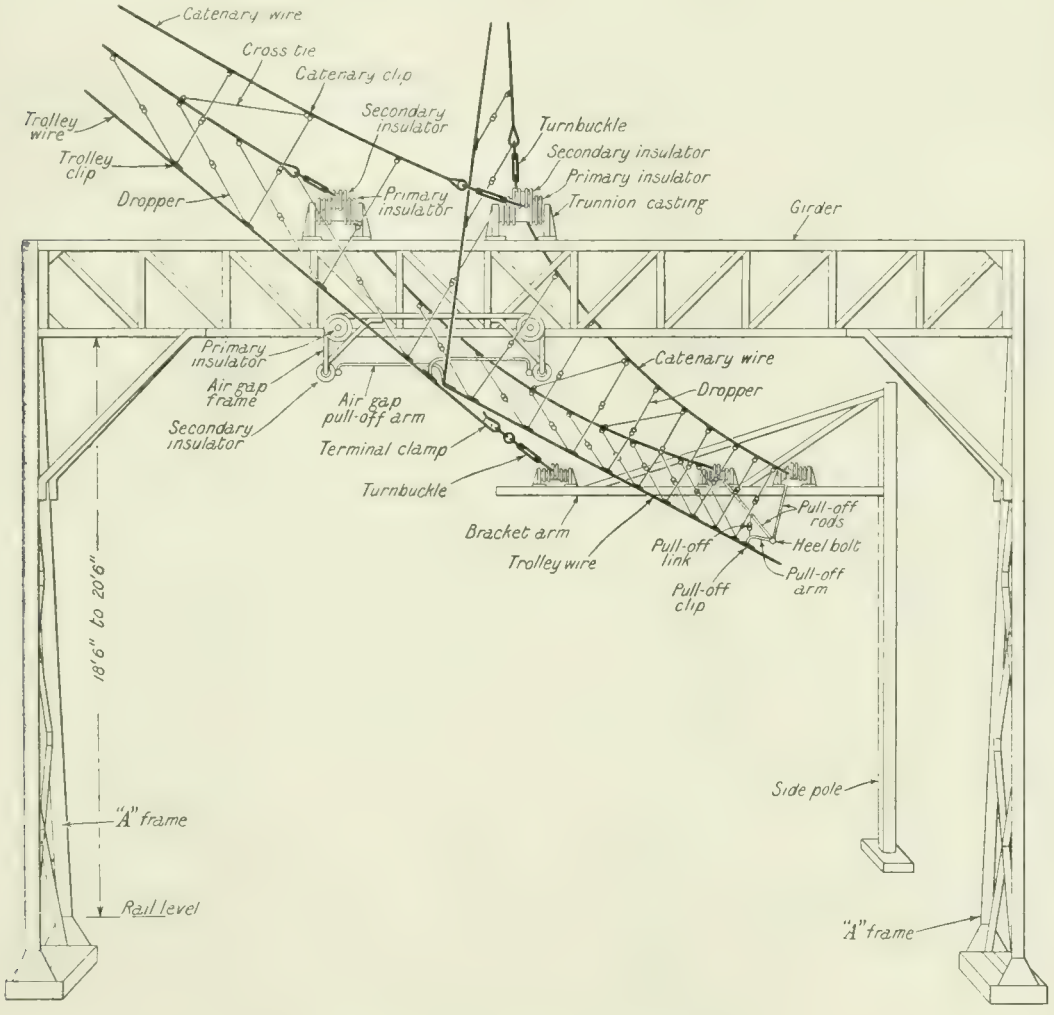


FIG. 1.—Overhead equipment: names of parts.

Distance between standards, 50 ft. to 210 ft.
Distance between trunnions, 2 ft. 6 in. to 7 ft.
Distance between droppers, 10 ft.
Size of trolley wire, 7/0 S.W.G.
Size of catenary wire, galvanized steel 12/13 S.W.G.
Size of dropper wire, galvanized steel 6 S.W.G.
Strain on trolley wire, 18 cwt. at 60° F.
Breaking strain of trolley wire, 22 tons.
Elastic limit of trolley wire, 19 tons.
Weight per yard of trolley wire, 2·26 lb.
Stagger of trolley wire, 9 in. from centre (existing).
Stagger of trolley wire, 12 in. from centre (proposed)
Size of pull-off rods, ¾-in. steam tube.

In 1907 when the first overhead lines for main-line purposes were being laid out in Germany, in the United States, and by the Brighton Railway, various principles of construction were adopted in order to fulfil the requirements mentioned above, and it is extremely satisfactory to be able to state that whilst considerable

Suburban Railway single insulation and a system utilizing counterweights for keeping up the tension of the trolley wire, both of which have proved unsatisfactory for such type of work.

In the United States they at first adopted an entirely rigid form of overhead construction, practically a

triangular girder, the three longitudinal members of which were the two catenary supporting wires and the trolley wires which were kept in position by tubular stays. It was found necessary to add a flexible wire under this triangular construction, as the solid conductor wire resulted in hammering and conduced to failures.

On the Brighton Railway the principles adopted in 1907 were :—

That the conductor wire should be as flexible as possible and that all hard spots should be avoided.

That double insulation was essential and that the mechanical as well as the electrical factor of safety of the insulators and overhead construction must be very considerable.

Provision was also made when designing the insulators that there might be no possibility of moisture or water collecting and freezing, thereby fracturing the insulation.

The general arrangement in use and the principal parts, as well as their chief dimensions and nomenclature, are shown in the accompanying isometric sketch (Fig. 1), which was prepared for the use of the employees of the railway so that they might be familiar with the names and uses of the various parts.

(B) Clearances.

Limiting factors in the erection of an overhead conductor system are the clearances at bridges, in tunnels and under any other structures, which are

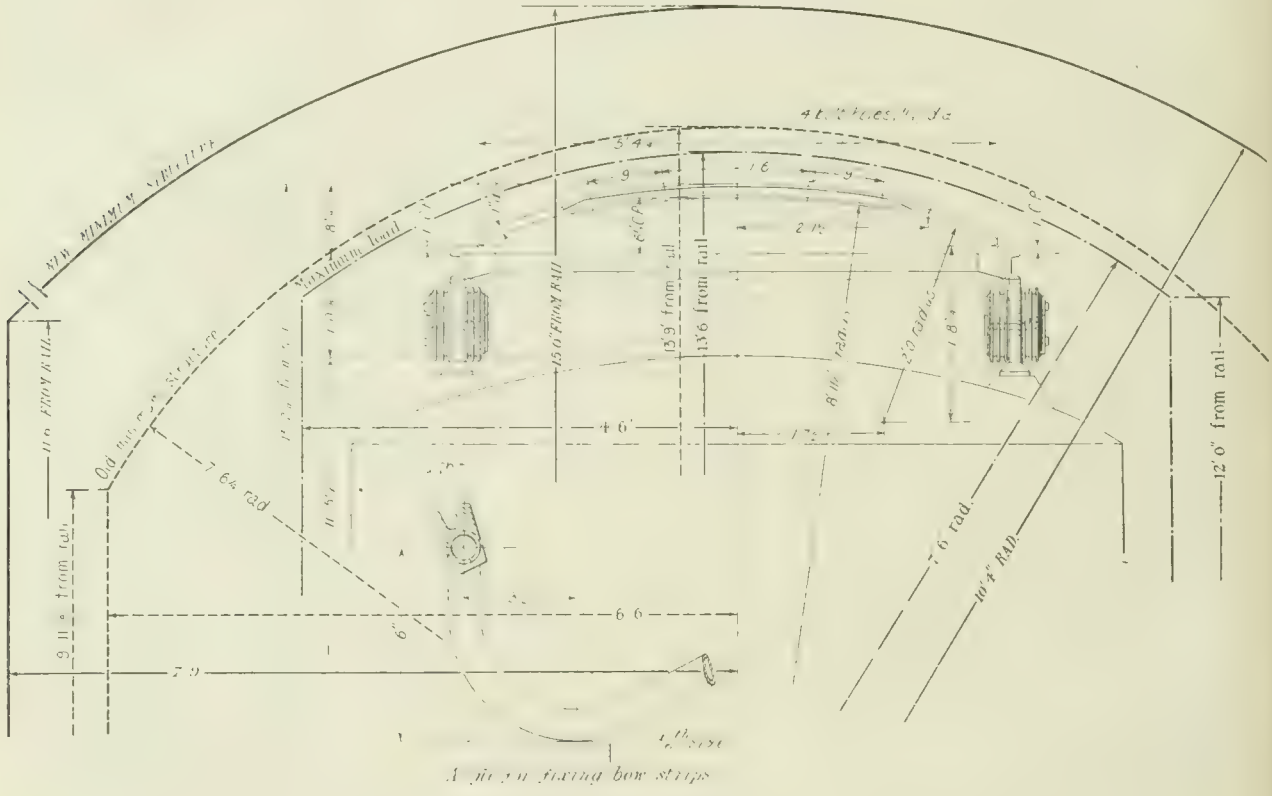


Fig. 2.—End view of bow gear showing clearances.

That all insulators should be placed in positions where they would be least subjected to the direct effects of the hot gases given off from the steam locomotives.

That, with the exception of complicated yards and cross-overs, the Up and Down lines should be sectionalized so as to be able to be cut out independently, whilst the complicated cross-over roads and yards were designed in such a way as to be sufficiently short to be coasted over.

That insulators should be only utilized under compression, and that elastic substances should always be placed between the insulator and its solid support, as well as between it and the mechanical construction which it supported.

necessary for electrical purposes, between the live conductors and the loading and construction gauges. Fig. 2 shows the various clearances existing to-day between the live portions of the bow gear, the loading gauge, and the old and new minimum structure gauges on the Brighton Railway. It will be seen from this diagram that the contour of the bow practically follows the contour of the loading gauge, also that under present conditions the ordinary running width of the bow is 18 inches, or 9 inches on either side of the centre line. This is the stagger at present adopted for the overhead construction on the Brighton Railway, although for the future, in consequence of the experience gained, this stagger will be increased to a maximum of 1 foot on either side of the centre line. The width of the

actual collector strip is 9 inches greater on either side of the centre line (in addition to the 9 inches allowed for stagger), or 18 inches in all on either side of the centre line, in order to allow for the rolling of the coach and for special conditions existing on very sharp curves, and this has been found ample in practice.

The general conditions of clearances which govern our construction are as follows:—

Height of live conductor above rail level.—The lowest live conductor on the L.B. & S.C. Railway is 13 ft. 9 in. above rail level, i.e. 3 inches above our loading gauge. This happens at Tennison-road Bridge, Gipsy-house Bridge, Boutflower-road Bridge, St. John's-hill Bridge (Up main), and Larkhall-rise Bridge.

This 3-inch clearance has worked quite satisfactorily, though, of course, a minimum clearance of 4 inches between the loading gauge and the live wire is worked to when possible. It is considered that 4 inches will be quite satisfactory for 11,000 volts.

Electrical clearances between bow gear and structure.—Four inches is considered to be the minimum vertical point-to-point electrical air clearance which should be allowed for voltages from 6,000 to 11,000; therefore a minimum of 4 inches vertically and 3 inches horizontally is provided from any part of the live bow to a structure at any height after the proper allowance for rolling has been made. The rolling allowance in the case of the Brighton Railway is 5 inches on either side when the centre of the bow is at 16 feet above rail level, which is the normal height of the trolley wire.

Electrical and mechanical clearances between overhead equipment and structures.—In this case it is also considered that the minimum point-to-point electrical air clearance from any live part of the overhead line equipment to the structure should not be less than 4 inches vertically and 3 inches horizontally for voltages from 6,000 to 11,000.

There is a case on the L.B. & S.C. Railway where a $2\frac{7}{8}$ inches air clearance has been running for a considerable period without trouble occurring. For a long time there were four places with a clearance of from 3 inches to $3\frac{7}{8}$ inches and no trouble occurred. Owing to improved construction, and for the sake of standardization, these places have recently been improved to give 4 inches clearance.

Minimum standard clearances.—Working on the principles given above we can get a flexible overhead line construction within a minimum of 10 inches from the loading gauge to the structure, i.e. within 14 ft. 4 in. above rail level, which 10-inch space is utilized as follows:—

4 inches—Air clearance between loading gauge and underside of trolley wire.
2 inches—Depth of flexible line construction.
4 inches—Air clearance between top point of live construction and structure.

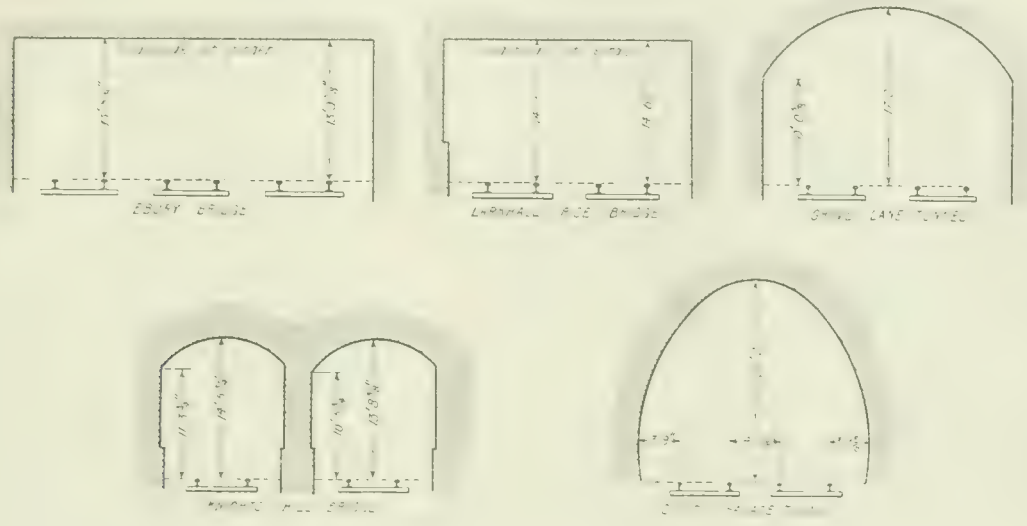


FIG. 3.—Examples of low bridges and tunnels on L.B. & S.C. Railway.

There are probably 20 cases of 6 inches overall from the underside of the live wire to the nearest structure, running satisfactorily to-day; and two of $4\frac{1}{2}$ inches where there is a short space of about 12 feet under the footbridges at Streatham Hill and West Norwood, in which two cases the "live construction" consists of a single trolley wire supported at either end of the bridge.

Fig. 3 gives the section and dimensions of some of the worst cases that have had to be dealt with.

In practice it has been found that there are a few isolated cases where the clearances required for a live conductor are not available and where the cost of alterations necessitated to procure these would be excessive and would not be justified by the results gained. On the whole of the running lines so far electrified, equivalent to 70 miles of single track, there are only four instances where sufficient clearances for

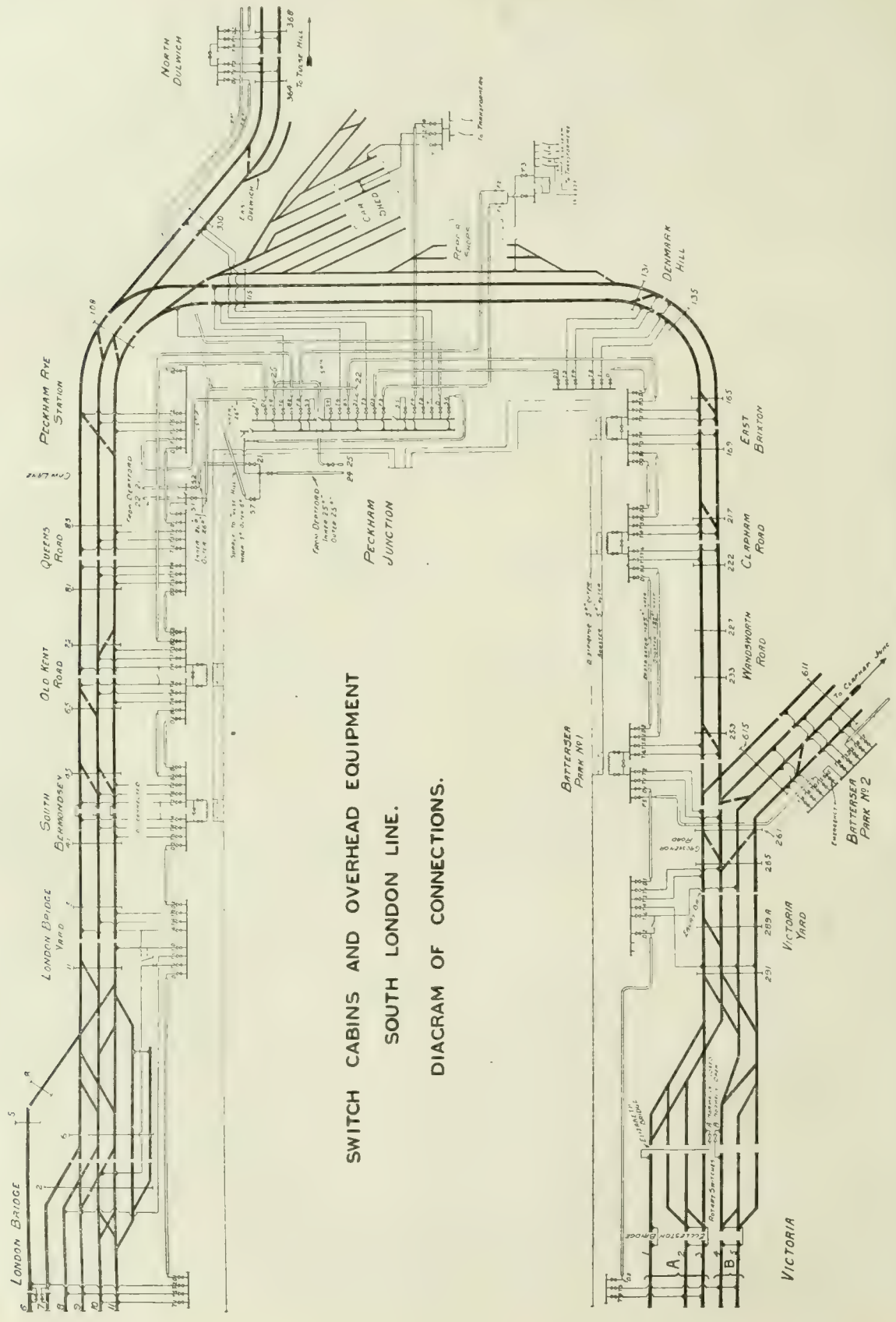


FIG. 4.—Diagram of connections, South London line.

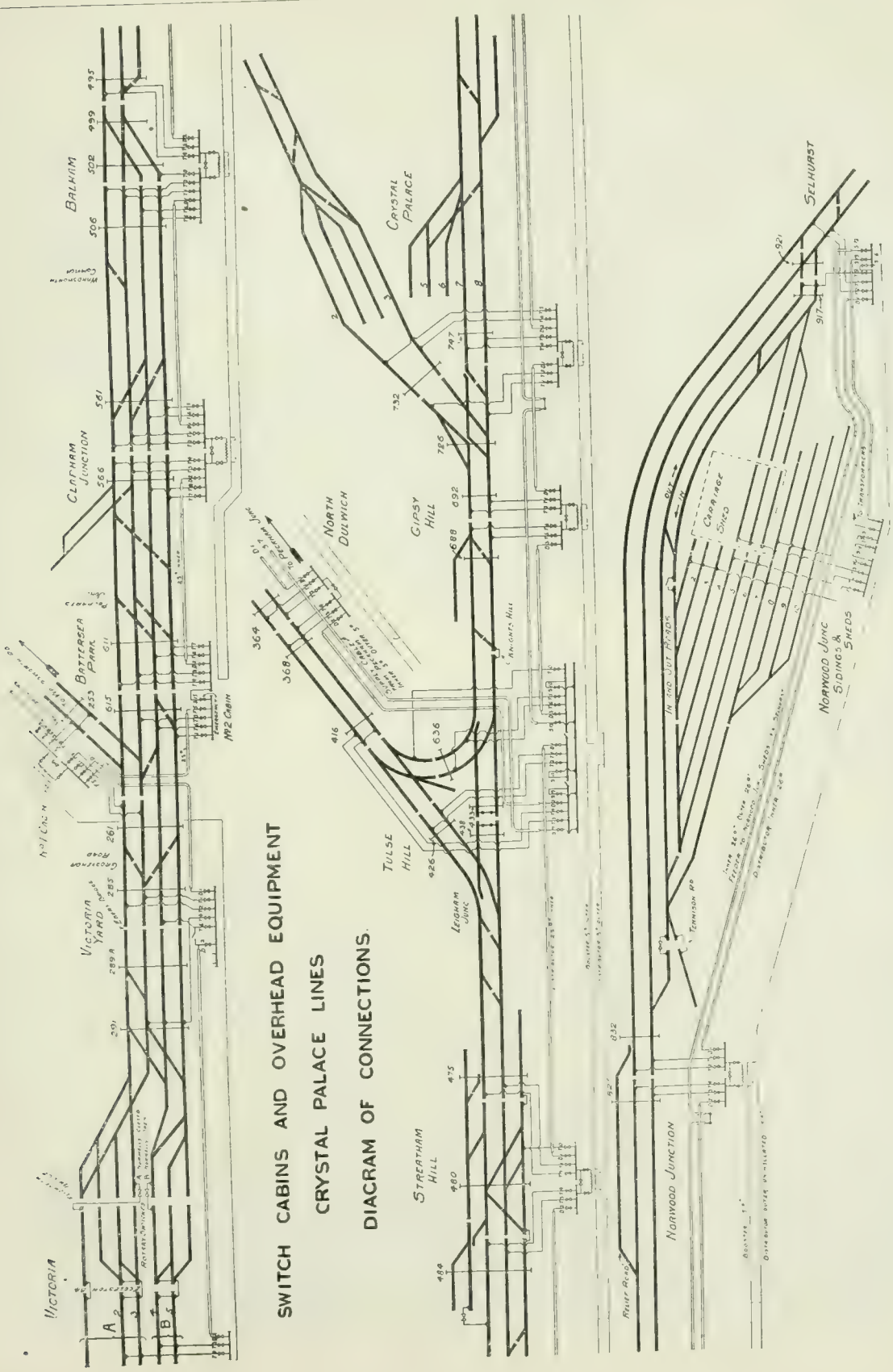


FIG. 5.—Diagram of connections, Crystal Palace lines.

a live conductor do not exist. Three of these occur at the bridges at the entrance to or in Victoria Station, where, owing to the lack of clearance, it has been found necessary to install earthed conductors. One of these bridges just outside Victoria Station—Ebury Bridge—is shown in Fig. 3 in section, and the two others are Elizabeth (see Fig. A, facing page 844), and Eccleston Bridges. Fig. C is a view taken from inside Victoria Station looking outwards, showing the bridges in the distance. The difficulty in this case is accentuated by the fact that owing to men having to circulate on the roofs of steam trains in Victoria Station, the height of the trolley wire inside the station is 19 ft. 9 in. above mean rail level, and the drop from this level to the level under the bridges is 5 ft. 10 in., which is dealt with at a gradient of 1 in 10, as the maximum speed at which the gradients have to be taken does not exceed 25 miles per hour. In order to avoid danger of short-circuits, a neutral section is interposed between the live wire and the earthed section under the bridge (see Figs. E and G). The contours of these sections have been designed in such a way that they take care of the inertia of the bow and the rapidity with which it rises and falls, with the result that there is practically no hammering of the bow when entering or leaving these sections.

One other bridge necessitating a dead section is on the Up side at Knight's Hill, close to West Norwood station, also shown in Fig. 3.

Another flat and very low bridge is Larkhall Rise on the South London line, shown in Fig. 3 and Fig. H, but in this case a live wire is carried through the bridge.

Another very low and difficult structure is Denmark-hill Tunnel, on the South London line, photographs of which are shown in Figs. F, J and K.

Other illustrations show Grove-lane Tunnel (Fig. L) at the other end of Denmark Hill, a very low footbridge (Fig. N) at Wandsworth-road Station on the South London line, which has had to be raised a few inches, two forms of overhead construction used under one bridge on the Crystal Palace line at Streatham-hill Station (Fig. O), Streatham-hill Tunnel (Fig. M) and the standard tunnel construction which has also been applied in the Crystal Palace and Knight's-hill Tunnels, also the entrance to London Bridge (Fig. P).

(C) Sectioning of System.

As has already been mentioned, the line has been divided into sections which can, if necessary, be isolated from each other with a view to locating faults and to minimizing any delay that might be caused thereby. The general system adopted is clearly shown in the diagrams of connections (Figs. 4 and 5), which represent every overhead conductor installed and the entire switching gear and distribution system used to feed and control the whole system.

It is obviously necessary to sectionalize the line, and the only satisfactory manner of doing this without limiting the speed at which trains can traverse such sections is by the use of air-gaps at the end of each section. Under ordinary conditions, and where there are no complicated crossings or junctions, this is a very easy matter, as one conductor can be brought to a terminal and anchored whilst another conductor is started at the point of section, so that the collector bow on a short section runs in contact with the conductor wires of two adjacent sections.

However, at certain points and crossings and complicated junctions this was found to be a very difficult matter. Both in Germany and in the United States this difficulty has been met by putting in section insulators mechanically connecting the adjacent sections. Experience has shown that this method caused flashing and knocking of the bow collector, causing complications and limiting the speed at which such connections can be negotiated. This difficulty has been entirely overcome by the special patented device designed for the Brighton Railway (see Fig. D, Plate II).

It has already been stated that whilst on ordinary running lines the Up and Down lines are easily sectionalized, there are one or two cases of cross-overs, junctions and the yards of terminal stations where this may become difficult, and the special air-gap insulator mentioned above has been of great assistance in overcoming such difficulty. Here the whole of the overhead line is electrically and mechanically connected and formed into what is known as junction sections. The entrance into such a junction section is shown in one of the lantern slides, and each of the junction sections is separately fed and controlled, as shown in Figs. 4 and 5. These junction sections are so laid out as not to exceed a length which can easily be coasted over should a defect render it necessary for one such section to be cut out.

(D) Maintenance.

In connection with the electrification of the Brighton Railway there is one section between Battersea Park and Peckham Rye on the South London line over which there is practically no steam traffic, and which is practically entirely operated electrically, whilst on the other electrified sections, and particularly on the Crystal Palace line there exists in addition to the electric service a very heavy steam service, which during the years of war was exceptionally heavy on the Crystal Palace line owing to the abnormally heavy munition traffic handled by the Brighton Railway.

As will be seen from the following diagrams which have been taken from the very careful records kept during the last 10 years, the maintenance costs and renewals of the overhead construction are very largely affected by steam operation.

The efficiency of the overhead system as regards the very small number of defects and delays arising therefrom is shown in Fig. 6. The larger number of defects in 1911 and 1912 over those in 1913 is due to the fact that the Crystal Palace line was opened in May 1911, before it had been really properly completed owing to the Festival of Empire, and the drop of defects in 1913 is due to these having been remedied. The rise after 1914 is entirely due to the War, owing to the heavy munition steam traffic over the Crystal Palace line. Even so the defects which caused delays exceeding half-an-hour are extraordinarily rare.

Fig. 7 shows the percentage of both the primary and secondary insulators renewed on the whole system per annum; whilst Fig. 8 shows the total number

Fig. A.—Elizabeth Bridge, Victoria Station.

Fig. B.—Victoria Station Yard.

Fig. C.—Victoria Station.

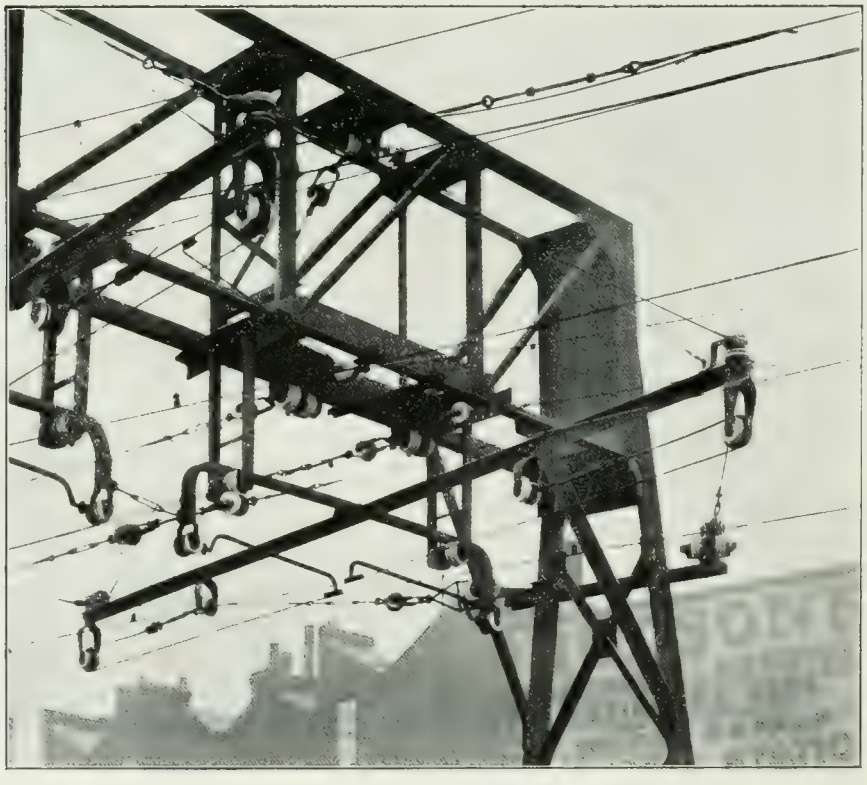


Fig. D.—Section Insulator, Victoria Station Yard

FIG. E.—Dead Section, Victoria Station.

FIG. F.—Denmark Hill Tunnel, Victoria Side.

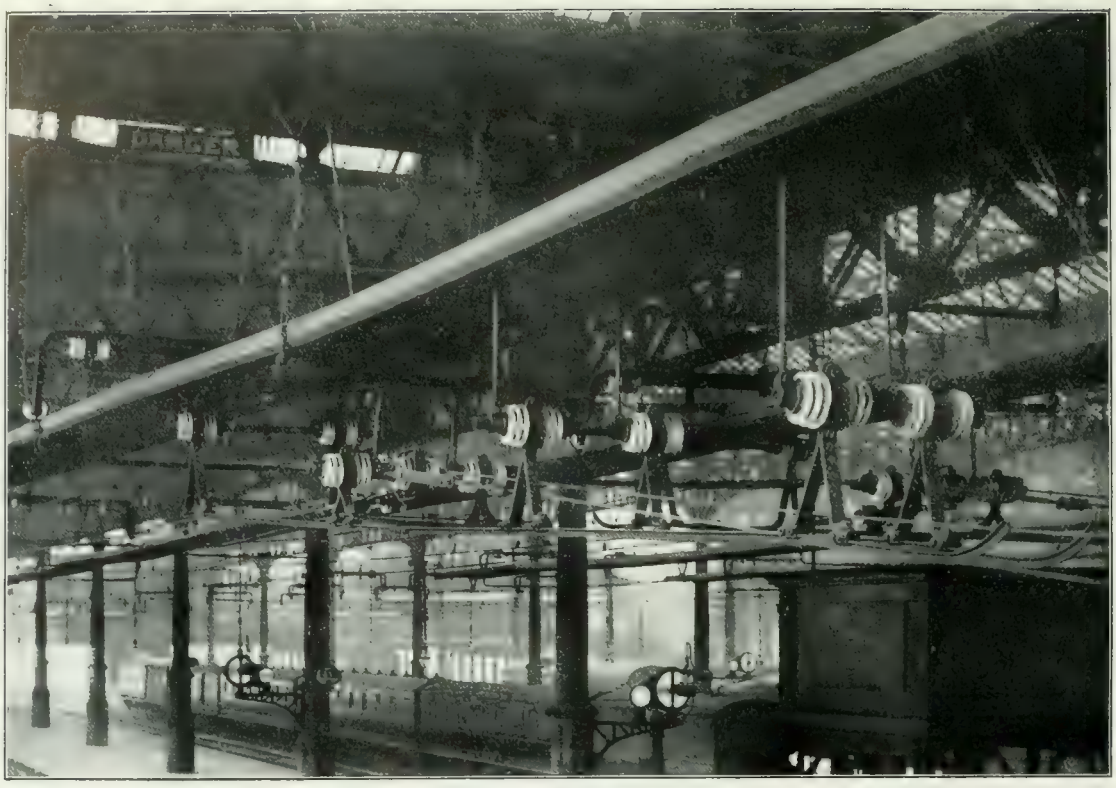


FIG. G.—Dead Section, Victoria Station.

FIG. H.—Larkhall Rise Bridge, Wandsworth Road.

FIG. J.—Denmark Hill Tunnel, London Bridge Side.

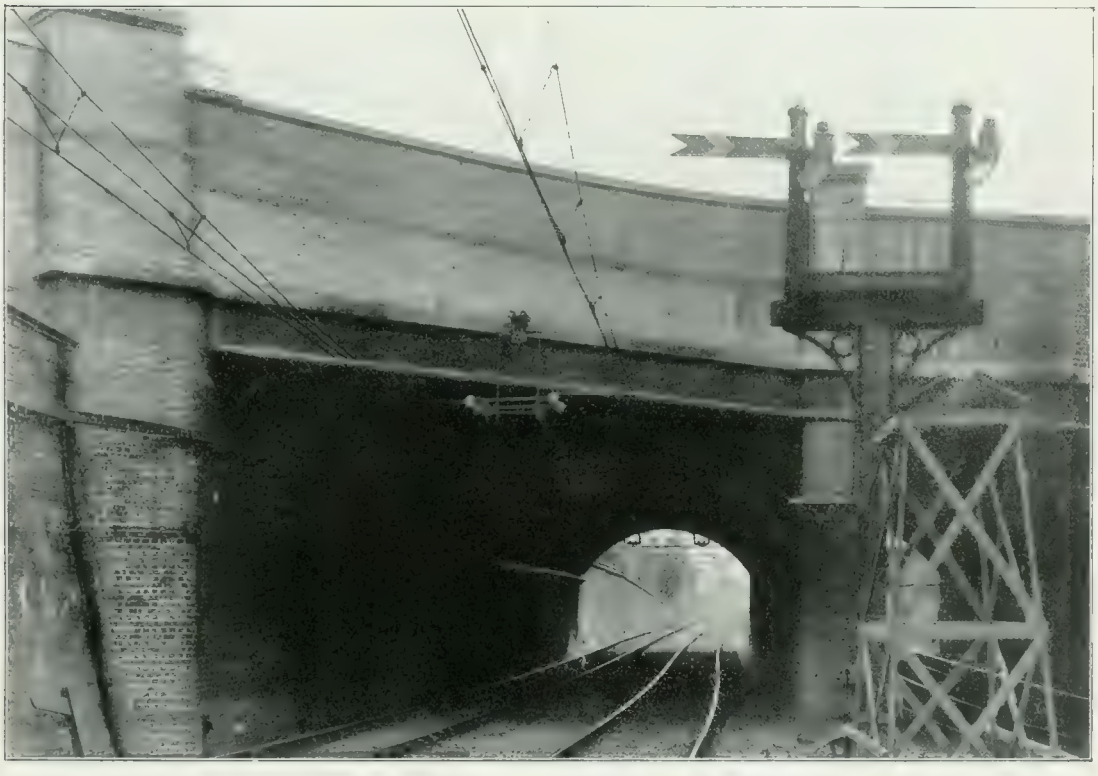


FIG. K.—Denmark Hill Tunnel, London Bridge Side.

Fig. L.—Grove Lane Tunnel, Denmark Hill.

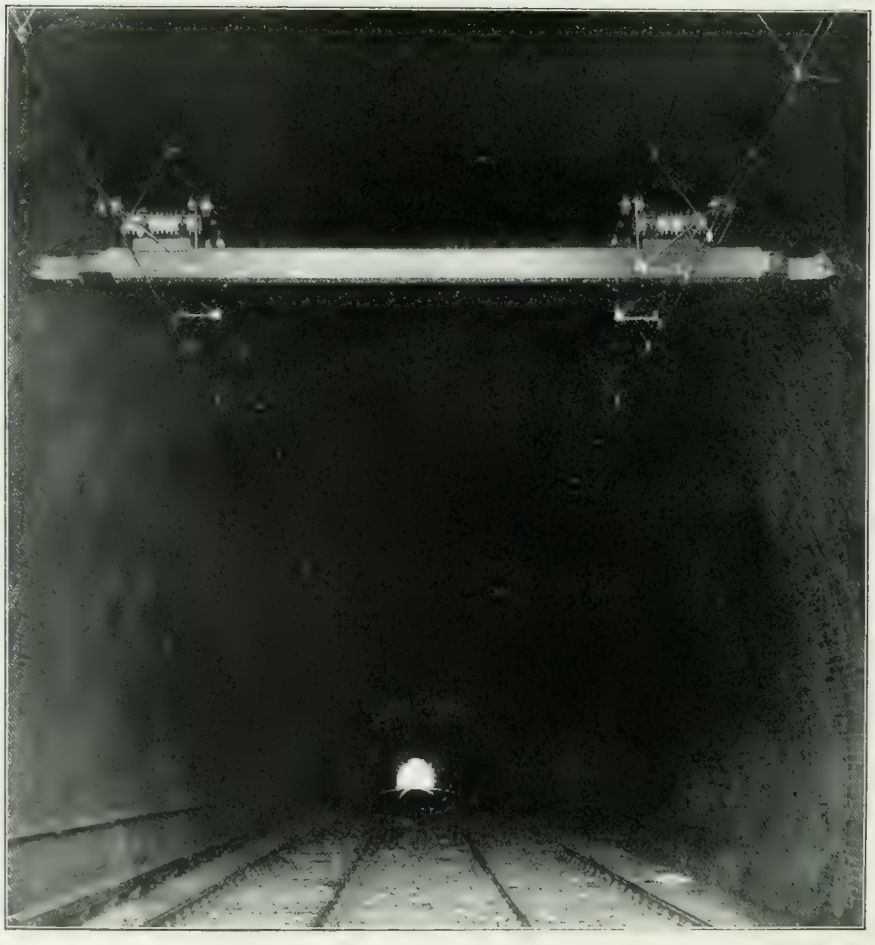


Fig. M.—Streatham Hill Tunnel.

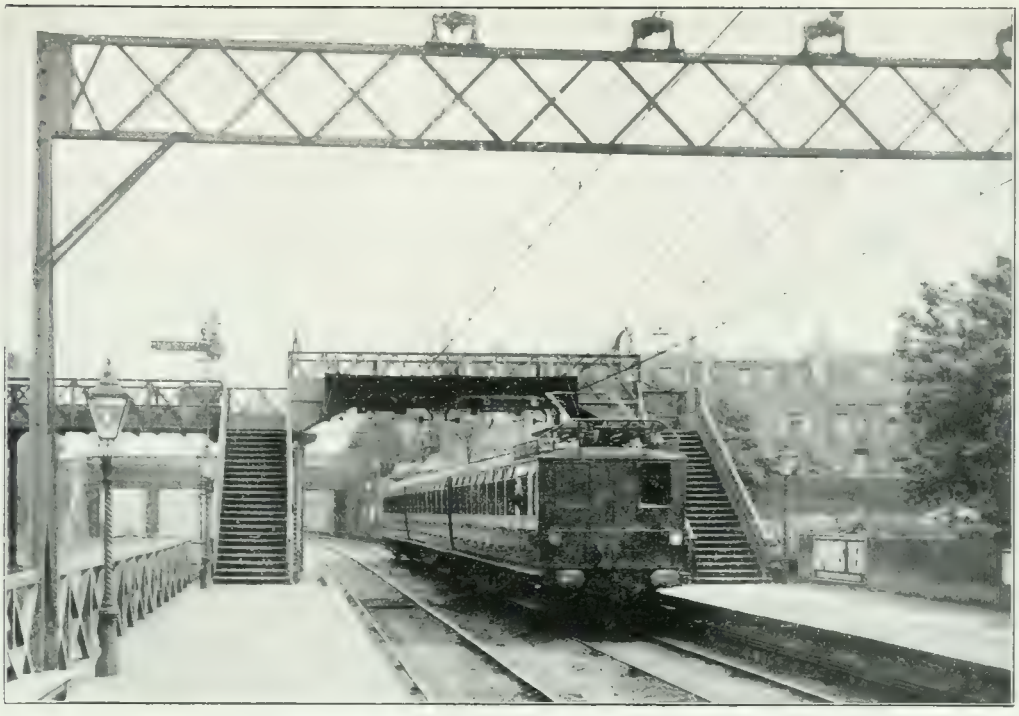


FIG. N.—Footbridge, Wandsworth Road Station.

FIG. O.—Bridge at Streatham Hill Station.

Fig. P.—London Bridge Yard.

Fig. Q.—Oak Point Yard; New York, New Haven and Hartford Railroad.

and percentage of primary and secondary insulators renewed on the South London and Crystal Palace lines.

It will be seen from the top figure of this latter diagram that not a single primary insulator has been renewed on the wholly electric section of the South London line. Considering that there are altogether 7,000 primary and 14,000 secondary insulators, the

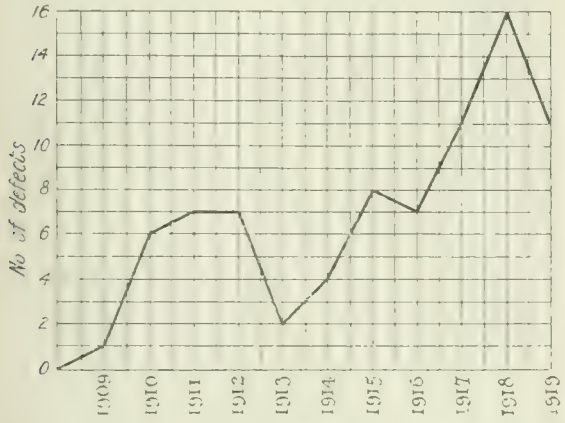


FIG. 6.—Overhead defects causing delays to traffic working exceeding 3 minutes.

result shown can be considered to be eminently satisfactory.

Fig. 9 shows the percentage of trolley wire renewed on the whole of the overhead system since it was first operated electrically in 1909.

As has already been mentioned the wear of the trolley wire is largely if not entirely dependent on the amount of current collected. This is borne out by

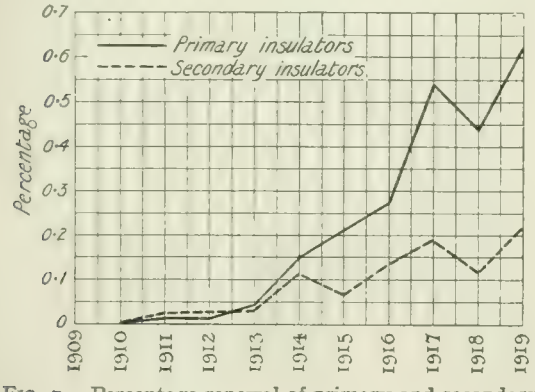


FIG. 7.—Percentage renewal of primary and secondary insulators per annum.

the actual measurements carried out during the last 10 years, the results of which are recorded in Fig. 10. It will be seen from the two top figures of this diagram that the wear on the trolley wire where no current is taken is nearly negligible, and the data given on this diagram are typical of measurements made at a very large number of structures at other places where no current is collected, and are borne out by the amount of trolley wire which has actually had to be renewed during the past 10 years.

That the wear is proportional to the amount of current collected is shown by all three diagrams in Fig. 10 and is corroborated by many other measurements made where heavy and medium currents have to be collected.

Figs. 11 and 12 show the percentage of catenary

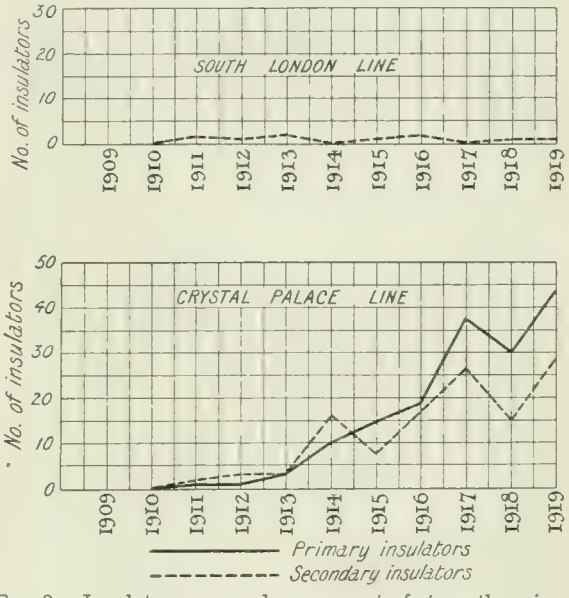


FIG. 8.—Insulators renewed on account of stone-throwing, electric, mechanical and steam causes.

7,000 primary insulators in use.
14,000 secondary insulators in use.

and dropper-wire renewals during the last 10 years. Here again the large increase in these renewals during the years of war is practically entirely due to the extraordinarily heavy steam traffic.

The influence of steam on the maintenance of catenary and dropper wires is clearly shown in Fig. 13. The top figure represents a typical 1-mile section of the

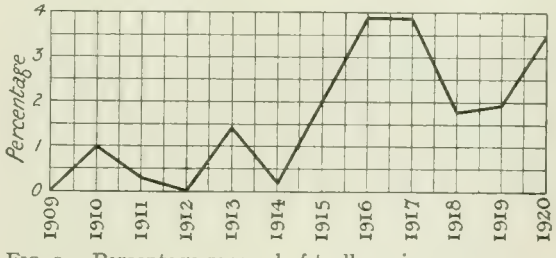


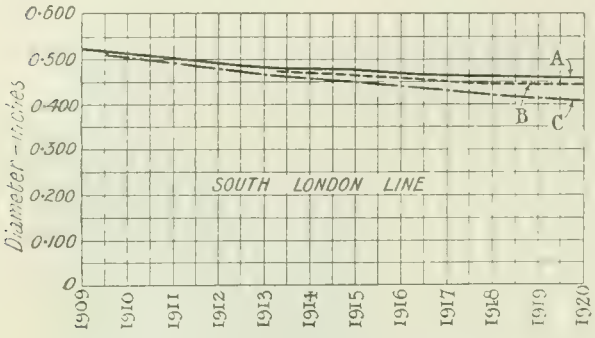
FIG. 9.—Percentage renewal of trolley wire per annum.

South London line, which is operated entirely by electric traction, where not a single catenary wire has been renewed. There are 150 miles of catenary wire, so that the amount renewed has been very small.

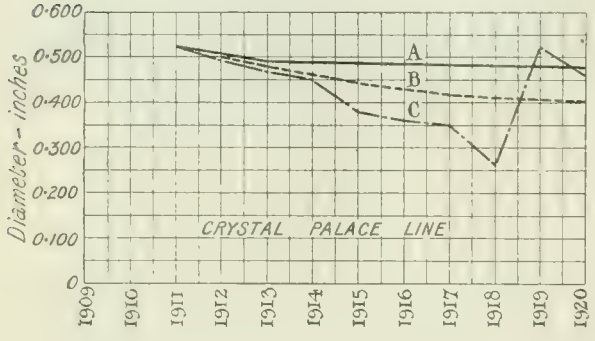
The two other diagrams in Fig. 13 show two parallel lengths of a mile on the Crystal Palace line, one with very little electric and very heavy steam operation and the other the Local line on which there is a mixed steam and electric service, from which it will be seen that the lines over which there is the greatest steam

traffic are subject to the greatest cost of maintenance.

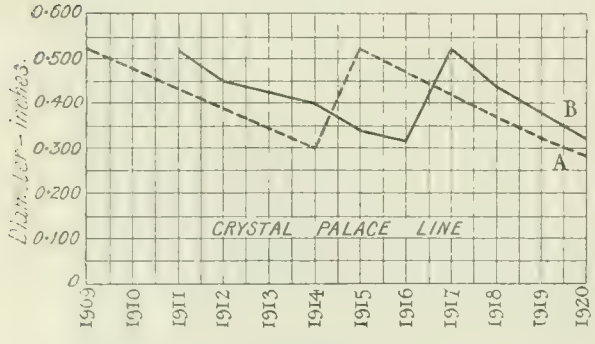
The experience gained on the Brighton Railway, where very great precautions were taken in order to ensure absolute safety of operation, has shown that a simpler form of construction and one which will



A. St. No. 214 Down line. East Brixton to Clapham road. No current.
B. St. No. 189 Up line. Clapham-road to East Brixton. Running current.
C. St. No. 170 Down line. East Brixton to Clapham-road. Starting current.



A. St. No. 666 Up line. Gipsy Hill to West Norwood. No current.
B. St. No. 587 Up local. Clapham Junction to Battersea Park. Running current.
C. St. No. 568 Up local. Clapham Junction to Battersea Park. Starting current.



A. St. No. 286 Down local. Victoria to Battersea Park. Lower part of Grosvenor Bank. Heavy running current.
B. St. No. 766 Down line. West Norwood to Gipsy Hill. Starting current.

FIG. 10.—Relative wear on trolley wire.

considerably decrease the cost of construction and maintenance can be adopted, and one has been designed and tried and will be employed in connection with any extensions which may be carried out.

(E) OVERHEAD CONSTRUCTION ADOPTED BY OTHER RAILWAYS.

Having discussed the overhead construction in use on the Brighton Railway for the last 10 years, a few illustrations of the systems adopted by other railways may be of interest.

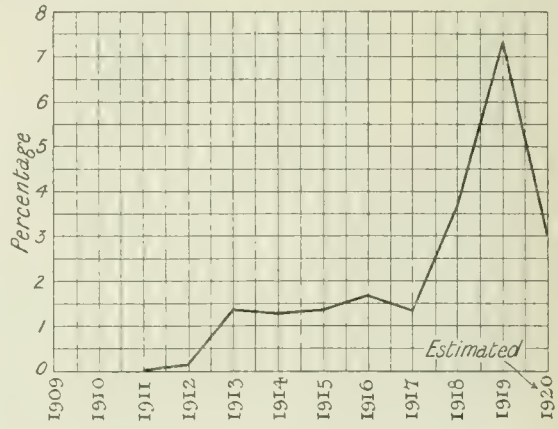


FIG. 11.—Percentage renewal of catenary wire per annum.

Pennsylvania Railroad.—Lantern slides show the straight line and curve construction adopted for the Paoli section of the Pennsylvania Railroad at Philadelphia, also the lines leaving Broad-street. This construction was completed in 1914–1915. It will be noted that a single catenary form of construction has been here adopted, which simplifies and cheapens the construction.

New York, New Haven and Hartford Railroad.—A lantern slide shows the triangular rigid construction

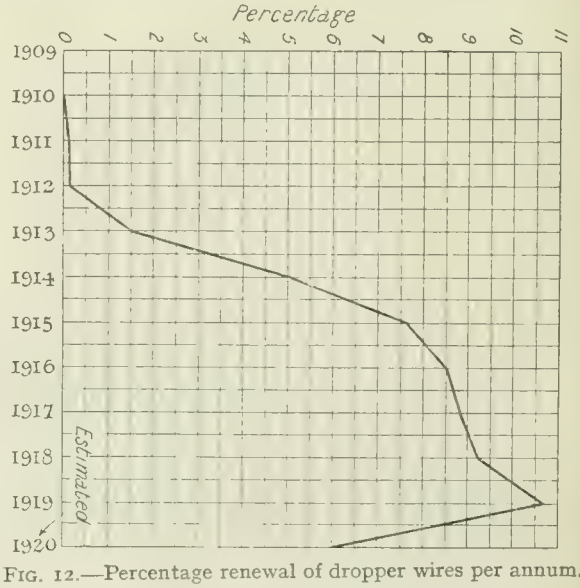
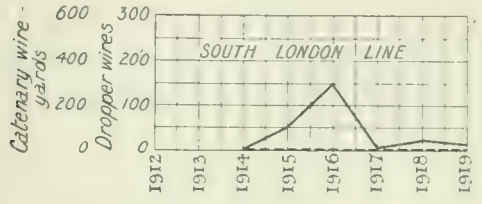


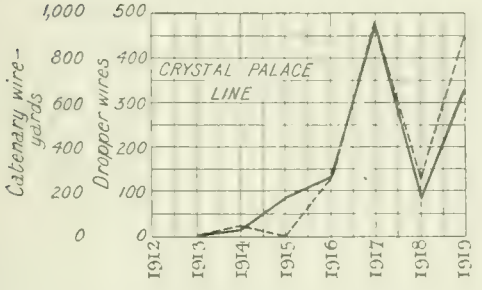
FIG. 12.—Percentage renewal of dropper wires per annum.

originally adopted, with the flexible wire which had to be installed later on underneath it. Fig. Q (Plate VIII) shows the biggest goods yard, in Haarlem, which has so far been operated electrically.

Prussian State Railways.—A lantern slide shows the construction adopted by the Prussian State Railways on their electrified lines.

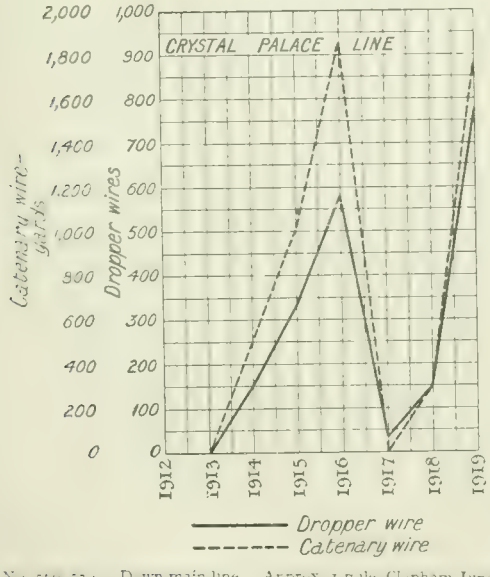


St. No. 150–185 Down line. Approx. 1 mile.



St. No. 560–530. Down local line. Approx. 1 mile, Clapham Junction South box to near Wandsworth Common station.

Heavy electric service; medium heavy steam, passenger and goods service.



St. No. 560–530. Down main line. Approx. 1 mile, Clapham Junction South box to near Wandsworth Common station.

About 1 per cent electric service; very heavy steam, passenger and goods service.

FIG. 13.—Relative renewal of dropper wires and catenary wires.

100,000 dropper wires installed.
150 miles of catenary wire installed.

Swedish State Railways.—A lantern slide shows the principle adopted by the Swedish State Railway.

CONDUCTOR RAILS.

(*a*) *General remarks.*—When we deal with the question of conductor rails, it may be observed that owing to the large mileage of these installed in this country there is a very considerable amount of information available regarding them which has been published from time to time both in papers which have been read before the various Institutions and in articles published in the technical Press.

(*b*) *Types of conductor rails.*—At the present moment there are three types of conductor rails in general use if we consider them from the point of view of form of current collection.

Over-running, where the shoe rests on the top portion of the rail, being kept there by means of gravity or springs, as is the case on the Underground Railway system, the London and South-Western, the North-Eastern, the London and North-Western, and the Lancashire and Yorkshire Liverpool–Southport line.

Under-running, where the current is collected from the lower surface of the rail, the rail being supported from the top and the contact being pressed upwards by means of springs against the conductor rail. This system is not at present in use in this country, although installed to a very considerable extent in the United States and on the Continent.

Side-running, such as was designed and installed by Sir John Aspinall on the Manchester–Bury section of the Lancashire and Yorkshire Railway, where the current is collected from the side of the conductor rail by means of a collector pressed laterally against the conductor rail by means of springs.

(*c*) *Some construction details.*—Conductor rails have to be interrupted at crossings and at complicated portions of the track, and in order to enable trains to leave and again make contact with the conductor rail at high speed either vertical or lateral ramps have to be installed to bring the collector shoe into gradual touch with the conductor rail.

Jumper cables have to be provided in order to connect electrically the different sections of the conductor-rail system, and experience has shown that where possible these should be laid either above ground or on the surface, so as to be easily accessible from the point of view of repairs and maintenance. Provision has also to be made by means of section switches or links to sectionalize the conductor rail so as to be able to isolate portions of it when required, in order to renew or repair portions of the track or in case of derailment.

The shape of the conductor rail varies very much and no standard exists for this at present, neither has any standard yet been definitely adopted by all railways for the height or actual position of the conductor rail.

The rails must be of a special chemical composition so as to give the highest conductivity consistent with durability.

Referring to the question of gaps, with pressures up to 1,300 volts no very great troubles with over-pressures have so far been encountered owing to contact shoes making and breaking contact, and it is therefore quite possible to coast over lengthy gaps where multiple-unit trains are used. This becomes difficult if not

impossible where electric locomotives are used to haul heavy loads and where a gap would mean a complete interruption of energy to the train. In order to overcome this difficulty, both on the New York Central and Hudson River Railroad and on the Pennsylvania Railroad, on complicated sections where the conductor rail has had to be interrupted an overhead construction to carry an overhead conductor rail has had to be installed.

With conductor rails operating at 600 volts, experience has shown that under normal conditions no protection is required or advisable, and, in fact, there are many cases where such protection having been originally installed has now been removed, not merely to reduce the cost of maintenance, but because it has been found that a conductor rail without such protection formed a smaller obstruction to the operating staff than a protected one. Notwithstanding the great mileage so far installed, the number of fatal accidents due to persons coming into contact with the conductor rail is very small, and such accidents have more generally occurred in the case of trespassers than of employees.

Where, however, a pressure of 1,200 or 1,500 volts is in use, the conductor rail must be protected, and a very suitable form of protection for a side contact has been adopted by the Lancashire and Yorkshire Railway on their Manchester–Bury section.

The most suitable material for this protection in this country has been found to be Jarrah wood.

Whilst on certain railways in certain cases it has been found necessary to anchor the conductor rail, experience on other lines seems to show that this is not always either necessary or desirable.

Insulators at present in general use are made of porcelain, earthenware, "Siluminite," reconstructed granite and various other substances, and the normal spacing is somewhere in the neighbourhood of 9 feet or 10 feet apart.

The only serious delays which have so far been caused in this country in connection with the conductor-rail system are in the case of those railways where top contact is made when abnormal weather conditions have caused the rail to be covered with a thin layer of ice. So far this difficulty appears to have been overcome either by under-running or by side-running.

As regards the question of wear and tear, it is very difficult owing to the varying conditions of climate, operation and location, to come to any definite conclusion, but experience in the open air on the Metropolitan District Railway would seem to indicate that the loss of rail due to wear and tear and corrosion may be taken at something like 1 lb. per yard per annum, half of which is due to wear and the other half to corrosion.

(*d*) *Systems for conductor rails.*—So far as the systems of conductor rail adopted in this country are concerned, it may be said that there are two definite principles at present in operation and a third has been proposed. In the case of the Metropolitan and the Metropolitan District Railways, owing to the fear of the drop in the return circuit being limited to such a figure by the Board of Trade as to make it difficult to realize with an ordinary track rail return, these railways have adopted double conductor rails, one positive and the other negative, the track rails not being utilized as a part of the return circuit. This arrangement has brought about certain defects in connection with insulation of the apparatus on the trains, particularly when the negative conductor rail becomes earthed from any reason, due to over-pressures. The necessity of using two insulated conductor rails obviously increases both the capital and maintenance costs of the conductor system.

The other system is that adopted by the North-Eastern, the Lancashire and Yorkshire, and the London and South-Western Railways, and is one where only one insulated conductor rail is employed, the track rails being utilized for the return circuit either with or without a supplementary bonded rail or return conductor. This additional rail is bonded to the track rails and serves merely for carrying current and is not insulated from earth.

With a view to getting the benefit of 3,000 volts pressure, but at the same time not having to utilize any motors wound for a higher pressure than 1,500 volts, and in order to do away with any large currents returning through the track rails, Mr. Raworth, the Electrical Engineer of the South-Eastern and Chatham Railway, has proposed the adoption of a conductor-rail system requiring two insulated conductor rails per track, the track rails serving as a neutral. A similar system has been running for some years on the Nord-Sud line in Paris which operates with an overhead conductor and insulated conductor rail, the difference of potential between these being 1,200 volts, and the track rails serving as neutral of a three-wire system.

Voltage-drops in Earth-return Circuits.

(*a*) *Direct current.*—The permissible voltage-drop in the earthed return is the most important factor in the case of direct and alternating-current systems of traction.

At the present time there have been very considerable departures from the original standard as dictated by the Board of Trade for maximum voltage-drop in rails of electric tramways where direct-current systems are concerned. The maximum allowance of 7 volts imposed on tramways has compelled such railways as have electrified under parliamentary powers, and who feared similar regulations being imposed upon them, to install insulated return-current conductor rails.

Other railways not so situated are operated with rail drops perhaps exceeding for short periods 20 times that figure. Either, therefore, the Board of Trade limit, as imposed on tramways, is unduly severe if applied to railways, or there is an amount of damage going on by way of electrolysis which must sooner or later involve considerable trouble.

Since substation distance, and therefore the economic operation of direct and alternating-current systems, are directly affected by rail drop, a time seems to have arrived when some decision should be taken on this point. The anomaly of one railway being afraid of

being limited to a 7-volt drop while another is unrestricted should be removed.

(*b*) *Alternating current.*—At one time it was considered that alternating current had no harmful effect so far as electrolysis was concerned, and in any case this effect is very small compared with direct current.

The Board of Trade has recognized that a higher pressure drop can be admitted with alternating than with direct current. The first regulation laid down was 200 volt-minutes for a period not exceeding 10 minutes, which means that for short periods the drop may be twice as much. The question of cost is very largely governed by the number of substations, and this in its turn is governed by the maximum drop allowed in the track return.

The limitations of rail drop are therefore governed by considerations of economy and of inductive effects. The latter have not proved by any means so troublesome as had been prophesied, the effects of rail impedance being largely counterbalanced by the comparatively small current transmitted in the alternating-current system.

Conclusion.

It is not the intention of this paper to make any comparison between the merits or otherwise of conductor rails and the overhead system, but merely to give information, particularly as regards overhead conductors, about which at the present moment very little is generally known in this country. It is, however, obvious that the presence of a charged rail near the track must increase the cost of maintaining the permanent way, and this is borne out by the fact that men working on track with a charged rail have been authorized to receive special extra pay at the rate of 2s. per week.

As regards overhead conductors, this difficulty is done away with except for the painting of the valances of the roofs at stations near which the live conductor passes. There will be a slight increase in the cost of painting these due to the presence of the live conductor, but this will obviously be insignificant compared with the increased cost of maintaining the permanent way due to the presence of the conductor rail.

Discussion before The Institution, 30 June, 1920.

The President (Mr. R. T. Smith): When electrification is carried out either by high-tension direct current or by alternating current, overhead conductors are essential in the case of alternating current and may be advisable for direct current, especially for sidings and at important junctions. They are essential for direct current when any pressure higher than about 1,500 volts is used, that being the pressure which is considered to be safe for a protected third rail, so far as our present experience goes. That being the case, the Institution is indebted to Sir Philip Dawson for having written a paper describing the principles and a great many of the details on which the overhead construction of the Brighton Railway has been carried out, an equipment which is probably unsurpassed anywhere in the world. Where steam traction during the war did not play havoc with the corrodible parts of that overhead construction, the cost of its maintenance compares very favourably with that of third-rail construction. An important part of the paper is the very full information given on pages 840, 841, and 844 as to the essential clearances between electrified metal and earthed metal, not only the trolley wire but the collector bows and their connections. The principle laid down that there should be an air clearance of 4 inches in a vertical direction and 3 inches in a horizontal direction, which I think fairly summarizes what the author has said, will probably be accepted everywhere as standard up to 11,000 volts. The section insulator mentioned on page 848 which is used on the Brighton Railway where an air gap cannot be adopted is of considerable interest. To my mind the most interesting parts of the paper, however, are the curves on pages 844, 845, 846, and 847, showing the percentage variation in maintenance costs with time. The general inference from these concentrated statistics is that the wear on the trolley wire is very small with the small currents which are transmitted at the high voltages used (6,000 volts), and also in general for the high voltages employed with single-phase collection. This is most clearly brought out in Fig. 10, and those of us who are interested in overhead wires for railway purposes can gain a large amount of information from a careful study of those diagrams. The effect that the amount of the current has on wear is to be remembered, and I hope it may be further brought out in the discussion. Another thing most clearly shown by Figs. 11 and 12, relating to the catenary wire and to the droppers carrying the trolley wire, both of which during the war have been subject to steam corrosion, is that where they are not subject to the effect of steam the renewals are very small indeed. In dealing with the third and fourth rails the author refers at the bottom of page 848 to the possible limitations of the amount of drop that is allowed in conductor rails, this limitation being imposed by a Government Department. Those railways that had the misfortune to electrify under a special Act had a clause about insulated returns in case of electrolysis or interference with other undertakings, and an insulated return was imposed on the District Railway. As a result all the other railways in touch with the District Railway—which means nearly all the 600-volt direct-current railways in the London district—were obliged to adopt a fourth rail between the tracks as an insulated return, so that their traffic might be interchangeable. Other railways that have been working under their general powers, i.e. which have not been electrified under special Acts, have, however, been using for many years quite large voltage drops, and I do not think there is any evidence in this country to show that drops of 150 or even 200 volts have caused or are likely to cause any damage, either by electrolysis or by interference with the railways' own or other people's property. This question

of pressure drop is very important in connection with the spacing of substations using direct current. I think we ought to try to get out of our minds the fact that railways are going to have anything in the way of difficult or impossible regulations imposed upon them with regard to pressure drop.

Mr. J. Dalziel: I want in the first place to say that I am giving not only my own views but those of my colleague on the Midland Railway, Mr. Sayers, who is unable to be present to-night, and also that they are our own and are not meant to represent any official view of the Midland Railway, though they do represent the result of a great deal of study of actual main-line conditions on that railway. An important statement in the paper is the report of the abandonment of the installations in the United States with conductor rails at 2,500 volts; of these I think there were two, one in Michigan and one in California. It would be interesting to hear more as to the causes of this. If safety, and ability to work the line, entered into it, I really cannot see where 1,500 volts should be better than 2,500 volts in these respects. Contact with 1,500 volts is not likely to be safer than contact with 2,500 or 3,000 volts; either is a fatal voltage. I do not see that the problem of insulation and protection will be appreciably less with 1,500 volts than with, say, 3,000 volts, and I am perfectly certain that the moral deterrent to efficient work, in maintaining the line, by which I mean the track rails as well as the conductor rails, will be no less with the one voltage than with the other. I think it is universally agreed that for main-line electrification 600 volts is too low, but on the one hand I doubt whether 1,500 volts is high enough to satisfy technical conditions, and on the other hand I am sure it is too high for use on a conductor rail under British main-line conditions. As the author contends in the conclusion of the paper, the experience of the Midland Railway on its electrified Tilbury section is that the presence of conductor rails does materially increase the cost of maintaining the permanent way, apart from the additional payment that has to be made to the men. From the main-line point of view it is perhaps not generally realized to what a very small extent really high-speed electric operation is extant. Experience of operating with a conductor rail at 70 miles per hour is practically non-existent. On a main line, and especially on such a main line as that of the Midland Railway, constantly intersected as it is by branches of all kinds, very frequent breaks in the continuity of the conductor rail are inevitable, and the constant engagement and disengagement of the shoe with the conductor rail make the success of high-speed working very problematical. Coasting can be successfully employed over conductor-rail gaps on purely passenger electrifications, or these are bridged by multiple-unit trains having a train busbar, but with locomotives it is quite otherwise. Not only so, but in operating freight traffic the gaps necessarily exist at the very points where the locomotive has to stop and reverse for shunting. In any case in sidings and shunting yards themselves a conductor-rail system cannot be employed, so that a hybrid system is inevitable. Conductor-rail gaps on the main line may also be, and in some lines are, bridged by an overhead section with a bow on the locomotive. If the bows are to be used to any extent, especially at high speed, I am afraid a good many of them will be wrecked by contact with bridges owing to drivers forgetting to lower them in time. We have similar occurrences with other apparatus. On main lines the location of a conductor rail in some tunnels is difficult; the work of permanent-way maintenance in long tunnels is already so exacting that the presence of a conductor rail is likely to increase this so as to make it possible to maintain only by adopting new and much more expensive methods. Again, tunnels generally drip from wall and roof to such an extent, and are so wet, that no type of protective covering to a conductor rail can be safely relied upon. In the opinion of my colleagues and myself the overhead system presents a much simpler problem, especially as our investigations tend to show that the difficulties of accommodating an overhead wire through the tunnels and bridges of a main line are not great. In most cases the presence of an overhead wire would not interfere with day-by-day maintenance to anything like the extent that the presence of a conductor rail involves. The overhead system need not be costly; simple construction will be not only cheaper but better from the point of view of operation, maintenance, and physical accommodation and location. Parts requiring painting, particularly such parts as can be reached for painting only from the tracks, should be reduced to a minimum, and from this point of view as well as from that of simplicity the Pennsylvania-Philadelphia span-wire construction shown in the paper appears to be the best design yet evolved. There appears to be a fear of using wooden poles in this country, but the average life of wooden poles is something like 40 years. Telegraph and telephone work is heavier and more exacting than contact-wire work, on account of the former's multiplicity of wires, which causes snowstorm trouble. The wear of the contact wire on the Midland Heysham line is somewhat less than on the Brighton line but is similar in proportion to the respective traffics. From considerations both of contact-wire wear and of reducing clearances, bow pressures should be kept low. On page 838 the author points out that, for overhead conductor operation, the currents to be collected must be relatively small, experience showing that heavy currents not only are difficult to collect but greatly increase the cost of maintenance. On the Chicago, Milwaukee and St. Paul line it has been established that currents can be collected at high speeds up to 2,000 amperes with a single bow. This is nearly double the amount of current likely to be required at 1,500 volts for any British locomotive in immediate view, but on the other hand it is collected by a bow with a double shoe from a double trolley wire. On this basis, at 1,500 volts, 750 kw. seems to be the maximum for a single shoe on a single wire. From the clearance point of view a double trolley wire will have some disadvantages here, and a double shoe appears likely to have too much inertia to be suited to the rapidly varying heights of contact wire which would be necessary on main-line sections as governed by bridges and tunnels on the

one hand and level crossings on the other. The total upward pressure of a double shoe will necessarily, for equal collecting power per point, have to be double that of a single shoe, and this will impose too much upward thrust on the contact wire. The same objection does not arise with respect to two separate bows some distance apart, but a single bow only is desirable. Apart, therefore, from any question of providing for future increases in the power of British locomotives, I think present-day requirements point to a higher voltage than 1,500 being used here, say 3,000 direct current. This may have to be paid for in, say, 10 per cent increased cost of locomotive equipment, and there may be also some increase in maintenance costs, though as a matter of fact the 2,400-volt Butte and Anaconda locomotives cost a good deal less for maintenance in 1919 than the 600-volt New York Central locomotives. Compensation for these increased costs, in greater or less measure according to line conditions, lies in reduction of substation expenses. Substation figures affect the subject of the paper, i.e. the contact system, in respect to their effect on the very pertinent and important point raised by the author as to rail drop. Main-line loads present characteristics very different from the steady load of a regular suburban service. Blocks on a main line are necessarily long, wayside shunting occupies the line to some extent and grades are frequently heavy. In a 5-mile section of a line carrying a fairly dense freight and passenger service, the load on a substation varies from nil to 4,500 kw. maximum with the no-load intervals extending from 1 hour to 1½ hours, and other 5-mile sections are similar with only somewhat lower maximums of 3,900 kw. and 3,700 kw. The load factor of a main line attains a very high figure taken as a whole, and that of substations improves greatly as the spacing is widened; the desirability of increasing the contact-line voltage so as thus to widen the spacing and improve the load factor is obvious. As the author points out, return rail drop imposes a distinct limit to this, which can only be relieved by providing feeders or boosting. It may be considered that the metal of an ordinary main-line railway with four 100-lb. rails is enough to provide carrying capacity for almost any load, but this is far from the case, and in the section of the line above referred to, with substations 15 miles apart, the return drop is excessive at 1,500 volts, reaching over 200 volts maximum, and rising to 40 to 50 volts maximum even with 5-mile spacing. Electrolysis troubles should be non-existent on a main line, for the sufficient reason that, generally speaking, water pipes are either non-existent or belong to the railway itself, which will see their usefulness disappear with electrification. Undoubtedly, therefore, a rail drop in excess of the standard 7 volts is permissible, and it would appear that a suitable value would be such as to be reasonably safe from the point of view of shock. On such a basis 100 volts as a maximum under the worst probable conditions would seem to be a suitable figure. It would undoubtedly be of advantage, as the author suggests, for some such definite figure to be standardized.

Sir James Ball: It may interest the members to know that we had to deal with some very difficult repairs to the Crystal Palace Tunnel during the war. This tunnel is in the London clay and in 1918, owing to severe side pressure, the invert was broken and it became necessary to rebuild about 120 feet of the tunnel in the centre. We had to keep the traffic going, and the method adopted, after consultation with Mr. Houghton, was to isolate the section in which the repairs were to be carried out by cutting out the live wire and erecting a dead section 140 feet in length, and in addition a neutral section 20 feet at either end. Lamps were suspended from the girders inside the tunnel with the letters "C" and "T" back and front to indicate the commencement and termination of the dead section. The repairs necessitated heavy timbering at intervals of about 5 feet, and the electrical system gave us the advantage of the electric light, which enabled us to complete the work much more rapidly than we should otherwise have done with acetylene lamps which we had arranged to use, and which render the atmosphere very bad. In this case the mere fact of having an electrified line resulted in a considerable saving of expenditure and increased the speed with which the work was carried out. I am not claiming this as being due to the overhead system, as no doubt we should have got the same result with a third rail, but as the engineer responsible for the maintenance of the track I should like to say I am very glad we had the overhead system.

Mr. H. E. O'Brien: From a railway man's point of view it seems to me that both the overhead system and the contact rail have serious disadvantages. The overhead system has the very serious disadvantage of the difficulty in finding places for the supporting structure. It would be very interesting if the author would tell us something of these difficulties as encountered by him. Will he tell us also what the tonnage of structural steel work per mile was and what percentage of the total cost of the electrification the overhead structure represented? As a previous speaker has said, English main lines are intersected with junctions, and that inevitably means in the overhead system a very large amount of special work. One of the things we all like to know before we start a job is, what it is going to cost. With the conductor rails the construction is so comparatively simple that we can tell what the cost is going to be within about 5 per cent before we start. Whether it is because we have a larger experience with the conductor rail or not I do not know, but I feel quite sure that with an overhead system a tremendous amount of survey work will have to be done, particularly on a complicated line, before an approximate cost can be reached. I think therefore we want more accurate data of the comparative cost of the two systems under similar conditions. I do not say it is a principal influence, but it is a very important one in connection with contact systems. The third rail is a decided nuisance to the railway staff. People who continually have to cross a third rail in the performance of their duties find it troublesome, and, though the 1,500-volt third rail has been made perfectly safe, I think there is no doubt that one is inclined to treat it with rather more respect than one would treat the 600-volt rail. I have

worked a great deal on 600-volt third rails, and I have walked occasionally over the 1,350-volt lines on the Lancashire and Yorkshire Railway, and it is noticeable that the ground staff treated that rail with rather more respect than they treated the 600-volt rail. There is no doubt, however, that the 1,500-volt rail is a safe and practicable proposition, but it would appear to be a great advantage if the guarding of the rail could be carried completely clear of the rail, so that there would be no possibility of getting shocks. When the guarding on a high-voltage conductor rail is new and clean, the shock that is got is practically a static shock; it dies away; but I am not at all clear that this is the case when the guarding has become thickly coated with carbon and sulphur deposits and brake-shoe dust. If 1,500 volts is to be used extensively on siding work, and there is no reason why it should not be on many classes of sidings, it is most important to reduce the possibility of even slight and harmless shocks to a minimum. It would be very interesting if some subsequent speaker would give information as to the extent of the shock that can be received under those circumstances. It would also be interesting, in connection with conductor-rail systems, if we could be told something about the success of the system on the Great Western Railway, where an inverted channel was used with the insulators projecting up into it. That has always appeared to me to be a very sound mechanical and electrical design of third rail. It has not been copied by anybody and there must be some reason for this, and it would be interesting to know it. While the principal objection to a third rail is its obstruction to the staff on the ground, it has been stated that the extra maintenance needed is also a disadvantage. The ground obstruction is not very serious, except where much shunting has to be done. Where shunting has to be carried out, if the shunting yard is not an extensive one, it is quite possible to put in wooden flooring level with the tracks, which only leaves the third-rail guarding projecting 4 inches above the flooring, and for ordinary goods shunting or carriage shunting the obstruction is not very serious. The increase in the cost of maintenance of permanent way should be negligible except when relaying. The problem of continuous contact with the third rail in main-line operations by locomotives is a really serious one, and it seems inevitably to mean the adoption of a hybrid system. With a reasonable length between the shoes of the locomotives, however, examination of any particular junction will show that the gaps are not numerous and that the amount of overhead construction is not likely to be very serious. I should like to ask the author to what extent he found the overhead work interfere with the signalling on the London, Brighton and South Coast Railway. How much re-arranging of signals had to be done and what did that re-arrangement cost? Was the re-arrangement of signals due to the necessity of moving them to find space for supporting standards, and how much of it was due to interference with the sighting of the signals by the structure? It seems to me that the railways with overhead structures have been fortunate in never having had a large length of their structure carried away by derailment. Cases have occurred where goods wagons and brake vans have been derailed and dragged distances varying from half to three-quarters of a mile before the driver of a long train became aware of the fact. It is quite conceivable that with an overhead structure such an accident may remove a very large number of standards and cause a very prolonged and serious interruption on a very busy main line. It must be admitted that in such a case the replacement would be a long job, whereas with the third rail the replacement is done very rapidly by the ordinary platelayer labour. The figures given as to the relative wear of the trolley wire seem to me very serious from the point of view of using a trolley wire for overhead work on direct-current lines, where the current may amount to 1,000 amperes. On the South London line the diameter of the trolley wire seems to have been reduced from 0·53 in. to 0·41 in. diameter, or 40 per cent in 9 years (see Fig. 10), while with starting currents the life is only 5 years, presumably this starting current being at the most 50 amperes per bow. That makes one think that the wear on a trolley wire with the heavy current that would be collected at 1,500 volts would be very serious indeed. The wear on a third rail does not appear to have any relation to the amount of current collected but to depend on the number of shoes passing over a unit length per annum. The life of a third rail is more dependent on the amount of CO_2 and sulphur compounds in the atmosphere than on wear; in a fairly pure atmosphere the life of a third rail is likely to be 25 to 30 years, and of the insulators 40 to 50 years. Everybody who has had experience of those railways where there is an unlimited pressure-drop on their return, knows that there has been no electrolytic trouble whatsoever so far as outside bodies are concerned, and I venture to hope the time is not far distant when all restrictions will be swept away and railways, which are in a different position from tramways, will be left quite unfettered in their selection of the drop allowed on their lines. The railway world is much indebted to the author for the very accurate information on minimum standard clearances, which will be most useful in connection with future electrification work.

Mr. H. W. Firth: The author has pointed out that this question of overhead conductor versus third rail is in reality practically one of voltage. It may be very difficult for us all to agree as to what is the satisfactory voltage for main-line work in this country, but I think it is beyond dispute that if we can remove from the track the obstruction of a third rail, particularly if two rails are necessary with direct current, this is very desirable. Mr. O'Brien mentioned that he always looks upon his 1,350-volt rail with a certain amount of respect. Personally I always look upon a 600-volt rail with a very great respect, and I do not trust the alleged protection on any of the third rails. It may be all right when first installed, but on a wet day I would not intentionally come in contact with the protection on a 600-volt rail. The only satisfactory third rail that I have yet seen is the inverted under-running third rail on the New York Central, which can be adequately protected because the insulator is between the inverted support and the third rail, and the cover-

ing board or guard is entirely clear and free from the rail. Any cover which is bolted to the rail I regard as an illusory protection altogether. The construction clearances in this country unfortunately are everywhere such as to preclude the use of such inverted rails. The suggestion due to Mr. Raworth, of the adoption of a three-wire system apparently having a 4-motor equipment and balancing the train equipment by having two conductor rails and the neutral to be formed by the track rails, is one which interests me greatly. That is a suggestion which I think is worth investigation. It seems to me, however, that if higher voltages are to be employed very small clearances between the shoe of one rail must result—the shoe, for example, running on the outer rail where the train crosses over to the inner rail at junctions. Clearances may be got in such places which are not adequate for higher voltages. I am glad other speakers have emphasized the point about the pressure drop in the return. It is highly desirable that something should be done to settle that question. Either 7 volts is right and should be insisted upon, or it is wrong and should be revised. There is one point I should like to ask the author with regard to overhead systems. I noticed some time ago on the Midland Railway at Heysham a rather neat example of overhead work having no pull-offs. I do not know if it has actually been in operation yet, or if the author has seen it, but if so I should like his opinion as to whether all the pull-offs and complications which occur in the majority of cases are necessary. I rather gather from the remarks in the paper that we can look forward to very great simplification in the overhead equipment. I think that is very important. I should like to mention, with regard to Mr. O'Brien's remarks on costs, that it is no good comparing the cost of an overhead conductor with that of a third-rail conductor. The cost of the job from the beginning to the end must be taken into account. It is no use talking about alternating current versus direct current, or about the extra cost of one motor against another, or of one conductor against another; the whole job must be taken as it stands. There is one thing which I should particularly like to emphasize, and which is illustrated by the author's lantern slides, namely, the question of big shunting yards. I regard that as a very important question indeed with regard to electrification in this country or in any other country. The amount of money which it is possible to save in these yards is very great indeed, and I cannot conceive how anybody is going to suggest—even with a floor-board within 4 inches of the conductor rail or anywhere else—that an important shunting yard where men have to run about and uncouple wagons can have any live rails on the surface. I think that is a very important matter which wants considering in the case of electrification of any line where there are very big goods yards and shunting yards.

Mr. G. L. Drury: The author has said very little from the rolling-stock point of view. I have here some of the contact strips which have been in use on the heavy electric locomotives now working on the North-Eastern Railway, which Sir Vincent Raven has kindly allowed me to show, and from which one can judge the amount of wear such strips get under very heavy work, sometimes as much as 1,000 amperes per locomotive. In the ordinary Continental type of bow, of which there are four per locomotive, the usual accelerating current is about 900 amperes, i.e. about 125 amperes per contact, and there are two overhead wires. It will be seen that the aluminium strips show very considerable burning. I may say that this strip has not been specially picked out, but was taken at random. The very great amount of punishment which these strips get in heavy traction work can thus be seen. One speaker to-night mentioned the Chicago, Milwaukee and St. Paul Railroad. I have brought a top contact piece with me from a bow which is similar to that used on that railway and it is obvious that the wear has been very considerable. There are copper contact strips and there are four points of contact for each, what I might call the pan. In addition there are two pans for each locomotive. So that in this case there are approximately 250 amperes per contact. It will be seen that the cutting is very severe on portions of this bow. The mileage for the Continental type of bow-strips before they have to be scrapped is about 7,000 miles. The cost of replacing these strips, which are of aluminium, and allowing for the scrap price of aluminium, is about £3 10s. to £4. We find that when the locomotives come into the sheds the sole repair necessary is to dress up these bows. I should like to ask the author if he has had any trouble from lightning. Protection against lightning is not mentioned in the paper. There are cases on record on the North-Eastern overhead line of both overhead equipment being damaged and also the equipment in the locomotive itself. It was nothing serious in the locomotive—mainly blow-out coils in the main circuit breaker. We are well equipped with lightning arresters, both on the locomotives and on the overhead line.

Mr. H. M. Sayers: I think the details of maintenance and replacement costs given in the paper are particularly encouraging. They show with respect to the items mentioned that the overhead system is distinctly an economical construction. The contrast between the rates of wear due to normal operation and the rates of wear due to corrosion caused by steam locomotive effects is very striking. The Brighton Company is to be commiserated with on the fact that it has had several miles of overhead construction standing for four or five years exposed to steam locomotive wear without the electric service being in operation. I can testify that on the Crystal Palace line the failures and delays which have been perceptible to the passengers have been negligible. One criticism which I feel inclined to make with regard to the Brighton railway construction is that it is heavier and more expensive than is really necessary in respect of structures and supports. That is particularly the case where the span is not so great as is required on a 4-track line. It looks as though the factor of safety adopted has been unnecessarily large. That is not a criticism to be unduly pressed. It was a pioneer installation and it was better to err on the side of safety than to risk breakdowns which would have discredited it; but only lines with a heavy service and large earning powers could stand the conse-

quent capital charges. A much lighter and cheaper construction is available for inspection on the Midland Company's line between Morecambe and Lancaster and Heysham. I saw that a long time ago and it looked extremely economical. It has given good results, but of course the traffic on that line does not compare with the traffic on the Brighton line, and whilst one would not like to say that because it has worked well there it would be justified on a main-line railway, it does show that a comparatively simple, light, and cheap structure can do the work. I quite agree with Mr. Dalziel that we have neglected the possibilities of wooden poles in this kind of work. Wherever I have used wooden poles for tramway work I found they justified the choice. The methods of dealing with small clearances used on the Brighton lines are admirably simple and ingenious. Applicability and simplicity are very important points in relation to the future of railway electrification. There can be little doubt that economical considerations will enforce the use of higher pressures than can be regarded as safe for third-rail conductors. The evidence of previous speakers as to the various kinds of drawbacks attaching to live rails adds an economical argument. There are one or two details on which the author is silent. Mr. Drury has mentioned bow wear. From the figures of the trolley-wire wear one may imagine that it is not very serious, because trolley-wire wear and bow wear are to some degree interlinked, but it is possible to sacrifice the bow to the wire to some extent, and that may be the correct policy, because it is obviously cheaper to replace contact strips than trolley wire. One would like to know something about the life of both and the expenditure on both. During the war it was reported that the Germans were using carbon blocks instead of aluminium contact strips, and that they got better results. That may have been propaganda, but it would be interesting to know whether any trials have been made here and what the results are. It would also be interesting if the author could give some information as to inductive interference between the Brighton Company's system and message wires in the vicinity, and as to the methods adopted in minimizing that interference. I have no doubt the Post Office has kept a sharp watch on the author. The effects, I fancy, are likely to be more troublesome on telegraph than on telephone circuits, because the frequency used is within the range of telegraph frequencies, especially Wheatstone frequencies, while it is a little low for audible frequencies. Very little information on this subject has been published, but I believe there is a good deal available. The Railroad Commission of California has published an enormous book on inductive interference, but it does not say one word about inductive interference from traction systems with message wires, except that it hopes to study the matter at a later date. All that it does give in about 1,100 pages relates to inductive interference between high-tension transmission lines and message lines. The effects of the overhead single-phase system are obviously rather complex. The electromagnetic effect is likely to be large, because the distance between the two conductors is large. The electrostatic induction is likely to be considerable and to increase with the pressure used. These two effects mingle; they cannot cancel out because they are not in phase. The relative magnitudes of each on different circuits differ greatly. It would be very interesting to know what the effects have been and what it has been necessary to do to remove them. The real question of overhead conductor versus third rail is that of the total economy of the job. It is not enough to say that one conductor system is cheaper than the other. With an overhead system a higher voltage can be used, so that in any case where transmission and distribution distances are considerable the overhead conductor has much in its favour, even if it costs more than the third rail. It has been alleged that the overhead installation does cost more than the third rail. That requires proof, and even if it is proved it does not settle the question. The author said that the fourth or return conductor rail was adopted on the London "Tubes" because of the limitations on rail drop imposed by the Board of Trade and the Post Office. I thought the main reason was the doubt about track circuiting if the track rails were used for the return.* That difficulty has been got over by using alternating current for the track signal circuits. I should like in conclusion to show three lantern slides of historical interest, namely, (1) Baltimore and Ohio "Belt Line" heavy-channel-iron overhead conductor for 600-volt supply to main-line trains. (2) One of the Baltimore and Ohio locomotives with pantagraph collectors. (3) Light overhead construction for single-phase working on one of the early German lines. The first two represent perhaps the most portentous overhead work ever erected. It was replaced by third rail shortly after the photographs were taken in 1900.

Mr. G. W. Partridge: I have watched the construction of the Brighton Railway overhead system carefully from its inception and I know the difficulties that have had to be contended with. I should like to ask the author whether he has had much trouble with the insulation of the line due to lightning, as I have often seen the effect of lightning causing short-circuits on the plant in the power station. There is another question I should like to ask the author: Has he ever considered a method of showing when one of the insulators has broken down? As there are two insulators in series it occurs to me that it might be possible to install some apparatus, such as a fuse or spark gap, which would come into operation if one of the insulators failed and would then indicate that the insulation of the line at that particular point was dependent on one insulator only. Owing to the small clearances on the line, particularly at the tunnels, I have often wondered why the system had not been changed from the overhead to the third rail by the use of a static transformer for reducing the pressure at the tunnels, so that the trains would run on the third rail in those tunnels where the clearances are so small. I am much interested in the wear of the contact bow submitted by the engineer for the North-Eastern lines. From the experience I have had in

* See Mr. F. W. Carter's paper on "Electric Railway Engineering" (*Journal I.E.E.*, 1906, vol. 36, p. 259): "The chief argument in favour of an insulated return is that it enables the track rails to be used for signalling purposes."

this matter the wear would be very much less with the alternating than with the direct-current system. I should imagine that the bow would last twice as long on the alternating-current system.

Lieut.-Col. F. A. Cortez Leigh (*communicated*): It is stated in the second paragraph of the paper that the 2,500-volt third-rail system tried in the United States (and which was, I believe, on a portion of the Michigan and Chicago Railroad) has been abandoned. It would be of interest to know whether this was due to difficulties in operating with a third rail at 2,500 volts or to other reasons, and, if the former, what were the particular difficulties experienced. The author mentions that an overhead conductor can only be utilized where the currents to be collected from it are relatively small. I should be glad to know what is the maximum current he considers it possible to collect from an overhead system, as I believe the double-contact sliding-bow collectors are very efficient and, with a double-contact wire giving four points of contact, any current likely to be required could be successfully collected. The curves given in the paper for the increased cost of renewals due to the working of heavy steam traffic beneath the conductors are most interesting and show in a very marked manner the desirability of keeping steam traffic off electrified roads. On page 846 the author states that experience has shown a simpler and cheaper form of construction can be adopted than that originally installed on the Brighton railway; it would be of service if the author would illustrate what he has in mind and also if he could state whether the span-wire construction used on the Pennsylvania Railroad has proved satisfactory in service. In common with other railways using top-contact conductor rails we have experienced trouble due to the formation of a thin film of ice on the rail under certain weather conditions. In order to clear this off before trains are put into service we have fitted a number of old coaching brake-vans with shoe beams to which is attached a steam jet nozzle (fed with live steam from the engine drawing the van) followed by a steel wire scraper and followed again by a rubber squeegee. This arrangement is found quite effective in clearing and drying the rail, provided the speed of travel is not too great. About 15 miles per hour is found to be a suitable speed. For dealing with ice and snow during the time the trains are in service we have fitted a large number of motor coaches with special sleet-cutting shoes having renewable hard steel cutter bars fitted diagonally into slots in a steel body. These shoes are used for collecting current as well as for clearing away the ice, and they are pressed down on the rail by a pair of spiral springs fitted over the shoe suspension links. With regard to loss in weight of conductors by corrosion and wear, our experience indicated that the heaviest corrosion was on a section of the line over which both steam and electric trains were worked, and it averaged approximately 0·82 per cent per annum. Tests had also indicated that the loss by wear was closely proportional to the density of electric train traffic over the lines and with our present heaviest service averaged 0·3 per cent per annum. On page 848 the author refers to the damage to insulation when one rail of a third- and fourth-rail system becomes earthed. I do not think the surge pressures are confined to systems using third and fourth rails and, further, our experience indicates that insulation defects most usually show up when the positive rail becomes earthed and not the negative as stated. It does not always follow that the capital expenditure is increased by the use of a third- and fourth-rail system. It is largely a question of the drop which can be allowed in the return conductor, the spacing necessary for the substations, and other matters. I agree with the author that the time has arrived when the question of the maximum drop permissible on the return conductors of railway systems should be gone into and definitely decided.

Mr. A. P. Trotter (*communicated*): The author appears to be under a misapprehension regarding Board of Trade regulations on rail drop. The 7-volt regulation was intended for tramway rails laid flush in streets containing water- and gas-pipes, and has never been applied to railways. It is, of course, largely exceeded on railways. I have often taken part in discussions on this subject.*

Sir Philip Dawson (*in reply*): As regards the remarks of Mr. Dalziel, I find myself entirely in agreement with all of them. The greatest fear I have in connection with overhead construction as regards maintenance and wear and tear is the question of the amount of current that has to be collected. We have no really extended experience with lines having a very heavy main-line service, so that it is very difficult to say what that wear and tear might mean in overhead construction with the low pressures where heavy currents have to be collected. I also agree with Mr. Dalziel as regards the mechanical difficulties of a hybrid system; of course difficulties are made to be overcome, but still the difficulties that will be encountered when, on a high-speed line, we have to pass from a third rail to an overhead conductor without any damage being done to the collectors, are serious.

With regard to Mr. O'Brien's remarks, I find it rather difficult at the present moment to give him a definite answer as to what the cost of steel structures or overhead construction would be, just as possibly it might be difficult to-day, with the varying conditions of the cost of materials and labour, to state what the cost of the conductor rail would be. I can tell him this: that, with the experience which one has, it is a comparatively easy matter, in laying out an overhead system, to fix a price. I think I should be quite willing to undertake to fix a price within 5 or 6 per cent for what an overhead construction under different conditions would cost, particularly as the experience we have had during the last 10 years has enabled a design to be prepared for overhead construction which practically is more or less independent of the obstructions, because it is possible by that to put up structures regardless of the exact position where junctions or points or crossings or anything of that kind have to be installed.

That brings me to a remark made by Mr. Sayers in connection with the solidity of the overhead construc-

* *Journal I.E.E.*, 1906, vol. 36, p. 267; 1909, vol. 43, p. 472; 1913, vol 50, p. 713; *Proceedings of the Institution of Civil Engineers*, 1907, vol. 167 p. 73, and 1915, vol. 200 p. 83.

tion used on the Brighton Railway. I entirely agree with him that it is a heavy form of construction, but it has withstood the test of service where other and lighter forms both on the Continent and in America have had to be substantially modified. I would, however, just bring out a point which I think he referred to, namely, that at the time the overhead construction was installed we could not take any chances. Therefore it was essential that the factors of safety, both mechanical and electrical, should be of such a nature as to make a failure a practical impossibility—all the more so because at that time it will be remembered that there was what was known as the battle of the third rail versus overhead. I am very glad to think that to-day part of the discussion anyhow has ceased to be a battle, and it is simply a question of the amount of current that has to be collected for the amount of energy to be delivered to a train, as to whether a low-pressure or a high-pressure system has to be adopted. The experience gained during the last 10 years has enabled the original construction to be simplified and improved in detail, and consideration is being given to possible modifications on the lines of the construction used for the Paoli electrification of the Pennsylvania Railroad, slides illustrating which have been thrown upon the screen and which resembles the construction experimentally adopted by Mr. Dalziel and Mr. Sayers on the Heysham line, which I recently had an opportunity, thanks to Mr. Sayers, of inspecting. With regard to the question of interference with signalling, we have been extraordinarily fortunate. We did anticipate that there would be a considerable amount of difficulty in sighting signals, but as a matter of fact, with the exception of having in a very few instances to put in repeaters, the signalling has not had to be altered at all. The difficulty experienced has been really surprisingly small. With regard to the insulation of the third rail at pressures higher than 600 volts and the question of the protection, I agree with what Mr. O'Brien has said. I certainly think that we have to treat the 1,500 volts with more respect and care. For myself I should very much hesitate to try and use anything more than 1,500 volts on a contact rail. The reason, as far as I have been able to get at the truth, why the 2,400-volt system was dropped on the Michigan Central was because very considerable trouble due to over-pressure was experienced. The breaking and making of a circuit at that pressure caused a very large number of the motors to burn out and gave a great deal of trouble generally. That I understand was the principal reason why that 2,400-volt third-rail system was dropped.

With regard to Mr. Firth's remarks, of course the question of the proper voltage for main-line working is an extremely difficult and thorny one. It would be very much nicer if we could use a very low voltage. If we could do everything at 600 volts, I think we should all prefer it, but, unfortunately, apart from other considerations the collection of the very large currents involved by main-line train operation compels us to go to higher voltages, and I am very largely in agreement with Mr. Dalziel that in any main-line electrification we shall probably have to go to pressures which will necessitate the use of overhead conductors. With regard to the question of the amount of current to be collected, it might interest the members to know that the normal current collected by one bow strip on the Brighton Railway, when running at full speed, is between 30 and 40 amperes, and the maximum current collected by a bow at starting is a little over 120 amperes. As regards bow wear, Mr. Houghton could give information. The cost of the maintenance of the bow strips is extremely small, particularly as when the bow strip is renewed the scrap aluminium fetches a very considerable price and is re-melted for making new strips. With regard to the very interesting photograph of the Baltimore and Ohio system exhibited by Mr. Sayers, I have also a photograph of that which I took about the same time or just before it was intended to take the construction down. I did not refer to it because I thought it would not be of very much interest, as it had proved a failure in consequence of the very heavy currents that had to be collected from it.

Mr. Drury and Mr. Partridge referred to damage by lightning. We have been extraordinarily free from any such damage. That more or less upholds the experience in America in connection with high-tension transmission lines—that the higher the pressure the less the danger of lightning. I cannot recollect having had a single insulator broken due to lightning. We have had considerable storms and we have had trouble in one of the auxiliary apparatus in the train. Our experience is that the lightning arresters on trains are really more troublesome than useful. Quite early in our experience—in fact, before the line was opened for public service in the early part of 1909—we did away entirely with lightning arresters in the trains. With reference to Mr. Partridge's question about the utilization of a transformer to bring down the pressure and enable a contact rail to be carried through tunnels where there is difficulty due to small clearances, in carrying through an overhead conductor that has been thought of a good many times, but it introduces the complication of additional cost in connection with the motor equipments, which, as they multiply according to the number of motor cars in service, makes it rather undesirable to install them if they can possibly be avoided. Whenever we can simplify we do so. Although it appears to be extraordinarily attractive on the face of it, in practice we have found that it is better to get over the difficulty by the devices we have adopted, rather than to put in a transformer.

(*Communicated*) Mr. O'Brien suggests danger to structures carrying overload equipment by derailment of vehicles. I think he will find that in cases of ordinary derailment the wheels seldom leave the sleepers, and damage to structures, whether signal posts, bridges or others, due to this cause, is comparatively rare. There have been numerous derailments on the electrified section of the Brighton Railway but no interruption of service due to damage of the nature suggested.

Mr. Firth draws attention to savings which may be effected by electric working in shunting yards. I agree that savings by electric operation of freight traffic are likely to be very large. I also agree that an overhead contact system is essential in the case of

shunting and marshalling yards. It is indeed this question which seems to necessitate a duplicate contact system where rail conductors are paraphased for general main-line railway operation. As regards the question of interference with telephone and telegraph circuits, I would refer those interested to a publication dealing very comprehensively with this subject and published by the Swedish State Railways.

Mr. Sayers asks whether carbon has been tried for bow collector strips. On the Brighton Railway carbon has been experimented with, but, so far at any rate, the results have been anything but encouraging. I agree with both Mr. Sayers and Mr. Firth that the cost per mile of overhead or rail conductors is by no means the sole, if indeed the principal, factor governing the adoption of one or the other.

It is interesting to learn from Colonel Cortez-Leigh that the effects of steam service are noticeable on rail conductors as well as on overhead construction. This emphasizes the "by-product" saving which would accrue in permanent-way and structure maintenance by the adoption of electric instead of steam haulage.

Mr. Trotter communicates a remark regarding the question of rail drop. Most of the contributors to the discussion agree as to the importance of this question and, although I am personally aware of the open-minded way in which Mr. Trotter has always dealt with matters such as this which materially affect electrical progress, the fact remains that the 7-volt limit still stands and might be insisted upon, and it is high time that it should be removed or modified.

THE APPLICATION OF THE ELECTRIC LOCOMOTIVE TO MAIN-LINE TRACTION ON RAILWAYS.

By Lieut.-Col. H. E. O'Brien, D.S.O., Associate Member.

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(1) History of Development.

The first instance of the use of electric locomotives on a large scale was in 1890, on the City and South London Railway. There was a tendency in this case to follow tramway practice by arranging the motors in each coach of the train, but this method was eventually abandoned in favour of the use of electric locomotives.

The locomotives of the Baltimore and Ohio Railroad, introduced about 1896, form the next notable instance of the extensive use of this mode of traction. These locomotives were employed to haul trains through the tunnels under the city of Baltimore, and were considered necessary on account of the difficulty in overcoming the problem of ventilation.

In July 1900, the Central London Railway was opened for public traffic, and the trains were hauled by electric locomotives in which the motor armatures were mounted direct on to the axles; this arrangement has, however, been abandoned owing to the pounding and vibration caused by the omission of bearing springs.

The North Eastern Railway in 1904 introduced their first electric locomotive for hauling goods and mineral trains on the Quayside branch line, which is mostly in tunnel and on a heavy gradient. In the same year the Metropolitan Railway was electrified, and the trains worked by electric motor cars. In 1907 electric locomotives were introduced for passenger and goods services.

In Italy, chiefly on account of the scarcity of coal, electric traction has been extensively adopted, and electric locomotives are very largely used. The Valtellina Railway was the pioneer line in that country and was opened for regular service in 1904.

In the United States, and especially in New York, the difficulty of tunnel ventilation was the chief factor determining the adoption of heavy electric locomotives.

The development in hydro-electric generating stations, and the success of electric locomotives in other spheres, turned attention to their use for heavy traffic on railways crossing mountain ranges, where tunnels are numerous, braking problems acute, and ample water power is available. This has been the case notably in Switzerland, where waterfalls are numerous, and in Norway.

In countries such as ours, where coal is plentiful and water power inconsiderable, electric traction for main lines has not made the same strides. Indeed, the only further development over what has already been mentioned, has been the introduction of heavy freight locomotives on the Shildon and Newport line of the North Eastern Railway in 1915, and one experimental locomotive on the Lancashire and Yorkshire Railway.

Although, as already instanced, the introduction of the electric locomotive in many parts of the world has been, in the first place, brought about by local conditions, the advantages following upon its adoption have been the cause of its rapid growth and application.

At the present time there are about 1,200 electric locomotives in service on the railways of the world.

(2) Effect of History and Locality on Lines of Development.

Development naturally was first on the lines of using two motor-car bogies with a superstructure containing electric equipment. As more powerful locomotives were required, difficulty in finding room between the wheels for geared traction motors as then designed, and lack of experience in gear design, led to designs with the motors placed in the superstructure and connected to the wheels by a linkage of rods, or with the motor armatures carried direct on the axle, on similar lines to the Baltimore and Ohio locomotive. The development of three-phase and single-phase motors by certain manufacturers helped this arrangement, as these systems did not lend themselves to compact designs, particularly if speed variation was to be obtained economically: improved design of direct-current motors accompanied by the use of better brushes, interpoles, field control and forced ventilation, led to a tendency to revert to the use of the geared direct-current motor, which has now become simpler to construct, more efficient, more flexible, more compact, and cheaper to maintain than the other types; e.g. commutators as now designed give practically no trouble, and brushes and contactors can run for long periods without attention. To illustrate the reliability of motors and equipment designed even so long as 16 years ago, the extension of the figures presented to the Institution of Mechanical Engineers by Sir J. A. F. Aspinall in his Presidential Address in 1909 are given in Appendix A, and the schedule of overhaul periods adopted on the Manchester and Bury line with the most modern designs in Appendix B. It may be mentioned here that the commutators of the Manchester and Bury motors give indications of having an indefinite life, while on the Liverpool and Southport line 90 per cent of the original commutators are still running. Desire for simplicity in the construction of the locomotive, a much extended knowledge of the design and manufacture of gears (the average life of the gears on the Liverpool and Southport line has been 300,000 miles,

and of the pinions 200,000 miles), and the necessity for preserving space in the superstructure for control gear, has also inclined designers in this direction. The original commitments of the great manufacturing firms, and the lines of research which they have followed, have had a considerable influence on the practice in different countries; generally the alternating-current motor driven by a rod linkage is the more favoured on the Continent, while the Anglo-Saxon opinion tends towards the geared direct-current motor.

(3) General Problem of the Design.

Electric locomotives fall into two main divisions: freight, the maximum speed of which need not exceed 45 miles per hour; and passenger, which must be capable of a maximum speed of 70 m.p.h. The characteristic torque of an electric locomotive, as compared with a steam locomotive, is such as to enable the draw-bar pull of the electric locomotive to be maintained at lower speeds in a way that is not possible with a steam locomotive. It is this characteristic that makes the high acceleration of the suburban electric passenger train practicable. In consequence, on a heavily graded line an electrically hauled train will maintain higher speeds on the up grade than the steam-hauled train, and will be equally fast, if required, down grade; hence, for fast schedules on lines with gradients, the electric locomotive need not be capable of as high a maximum speed as the steam locomotive, and in fact it is found that owing to this characteristic the introduction of the electric locomotive on a line containing grades enables a 20 to 30 per cent faster schedule to be maintained. The increase in schedule is also partly due to the possibility of regenerative braking, and to a small extent due to the more rapid acceleration of the train from rest. High maximum speeds have been attained with electrically driven motor bogie coaches, the classic example being the coach used in the Zossen experiments when a speed of 120 m.p.h. was obtained with a coach carried on two six-wheel bogies: on the Liverpool and Southport line and the Manchester and Bury line 60 m.p.h. is attained with perfect steadiness, in the former case on a road bed with a sand foundation. When the bogies of such a vehicle are placed closer together and carry a heavy superstructure, as in a locomotive, the natural period of the whole vehicle is increased and oscillation tends to occur at high speeds (an elaborate mathematical investigation of the conditions causing these oscillations was given by Mr. Carter in the *Proceedings of the Institution of Civil Engineers*, vol. 201); it has therefore become general practice to provide high-speed electric locomotives, whether the driving wheels are carried in a fixed frame or whether they are carried in bogies, with carrying axles fore and aft, either of the pony, radial or bogie type, whereas practice again has shown that for goods locomotives no carrying axles are necessary. Excessive wear on curves due to the low centre of gravity of the motor bogies of suburban electric coaches, has led to a desire to raise the centre of gravity of the bogie, and incidentally of the whole locomotive. The height of the centre of gravity of a motor bogie coach is 43 inches, whereas that of a steam locomotive of comparable power is 58 inches. As long as the geared design of motor is adhered to, the only possible method of increasing the height of the centre of gravity is to rotate the motor into a vertical position. In the case of a 250-h.p. motor on a 42-inch wheel, this involves carrying a dead weight of approximately 4 tons on the axle, instead of 2 tons as in the case of nose suspension; a compromise is to tilt the motor at 45°. By the use of a quill the motor weight can be entirely spring borne, but at the expense of complication of moving and therefore depreciating parts.

This design is comparatively untried and little is known about its maintenance costs. In any case the room required in the superstructure for brake pumps, heating apparatus, resistances, circuit breakers, contactors, and controllers, all of which need more maintenance and more constant examination than the motors, in the author's opinion preclude any greater raising of the centre of gravity than is given by tilting the motors

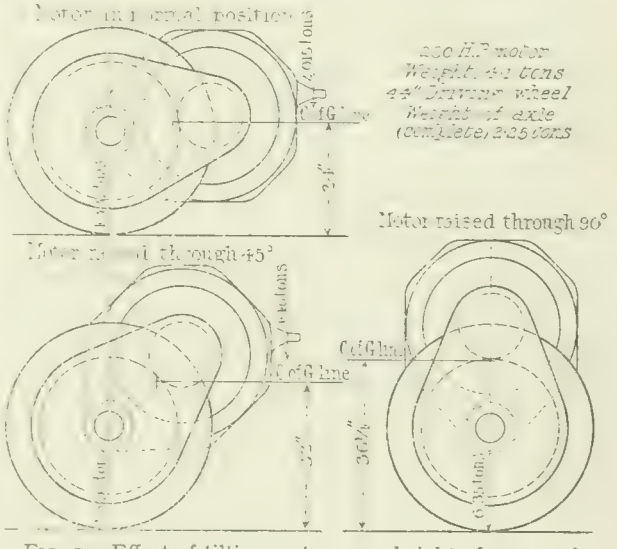

Fig. 1.—Effect of tilting motor upon height of centre of gravity and height of driving wheel and bogie.

to 45°. The effect on the weight distribution is shown in Fig. 1, a 25 per cent increase in the height of the centre of gravity of wheel axle and motor resulting in only a 13 per cent increase in the dead weight on the axle.

The total weight of four 250-h.p. motors would be approximately 17 tons. The total weight of a locomotive equipped with four such motors would be approximately 72 tons; the motor weight is therefore approximately 25 per cent of the total weight. The effect of raising the centre of gravity of motors on the resultant pressure on outer rail is shown in Fig. 2. As the electric locomotive will in general be designed with a 58-inch wheel to obtain better adhesion, form of tooth in the gearing, and lower journal speeds, this in itself raises the centre of gravity of the motors by 8 inches as compared with the usual motor bogie design for suburban services in which a 42-inch wheel is the maximum diameter used.

It should be noted that if the motors are carried on

bogies, the bogie tends to behave as a separate vehicle so far as lateral movements induced by a low centre of gravity are concerned. The raising of the centre of gravity is therefore more important in the bogie type of locomotive than where motor axles are carried in frames to which the superstructure is rigidly attached.

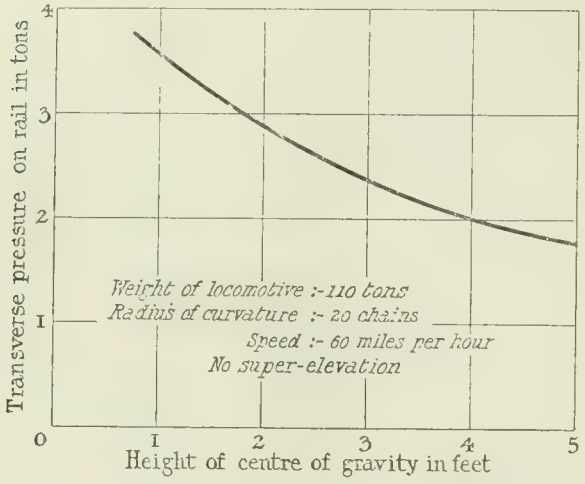

FIG. 2.—Effect on transverse pressure of heights of centre of gravity.

The use of bogies carrying motors, so far as high-speed electric locomotives are concerned, appears to the author to involve an unnecessary complexity for any 4-motor unit, as the rigid wheel base in such a case will not exceed that of a 0–8–0 steam locomotive, while a larger degree of side play in the boxes will be permissible first instance, by the strength of the couplings, and by the limitation imposed on the length of the trains by the available accommodation at loops and terminals. The maximum tractive effort, maximum horse-power, and maximum tractive effort at maximum horse-power, are given in Table I for the 4–6–0 and 0–8–0 locomotives of the Lancashire and Yorkshire Railway, which are fairly representative of English railways generally, as compared with similar data for various types of electric locomotives. This table also gives the breaking strength of wagon and carriage couplings respectively.

Reference to Table I and to the curves given in Figs. 3, 4, 5, 6 and 7 shows that the maximum steam locomotive draw-bar pull occurs at starting, and falls off continuously with increase in speed, whereas the maximum draw-bar pull can be maintained in the electric locomotive up to one-third to a half of its maximum speed. Higher speeds on up grades can therefore be maintained with the electric locomotive without increase in the maximum draw-bar stresses imposed on the train couplings. The maximum draw-bar horse-power of these typical powerful British steam locomotives in the above table does not exceed 900 h.p.; it may therefore be safely assumed that for many years to come no electric locomotive exceeding 1,500 draw-bar continuous horse-power will be required on English railways. It may be further assumed that no motor exceeding 250 h.p. is likely to be required for British railways, as a combination of six such motors will give 1,200 draw-bar h.p., or two four-motor equipments in multiple unit will give 1,600 draw-bar h.p.

With a geared motor, while there is no practical limit to the upper gear ratio, the lower gear ratio is

TABLE I.

Type	Rated h.p. Motors	Cylinder Diameter, Stroke and Heating Surface	Wheel Diameter inches	Max. Tractive Effort, tons	Tractive Effort at max. h.p., tons	Max. h.p. at Draw-bar	Speed at Max. Draw-bar h.p., m.p.h.	Max. Speed 150-ton Train on Level, m.p.h.	Breaking Load Couplings, tons		Remarks
									Carriage	Wagon	
4–6–0 steam ..	—	16 in. × 26 in. (4 cyl.) 2,507 sq. ft.	75	9·7	7·4	915	32	54	31·25	63·4	—
0–8–0 steam ..	—	21½ in. × 26 in. (2 cyl.) 1,944 sq. ft.	54	10·6	11·4	865	20	32	31·25	63·4	—
2–6–6–2 6 250-h.p. motors	1,500	gear ratio 2/1	58	8·25	8·25	1,860	38	51	31·25	63·4	Full parallel
2–6–6–2 6 250-h.p. motors	750	2/1	58	8·25	8·25	880	18	35	31·25	63·4	Series parallel
2–6–6–2 6 250-h.p. motors	1,500	4/1	58	16·2	16·2	1,820	19	34	31·25	63·4	Full parallel
4–4–4–4 8 150-h.p. motors	1,200	1·93/1	42	6·6	6·6	775	20	52	31·25	63·4	Multiple unit motor cars

than is the case with the steam locomotive with coupling rods. Where it is desirable to use 6-motor units, an articulated 2–6+6–2 design should be cheaper to build and give better results in running than a similar design with a loose superstructure carried on bogies.

The maximum power of the steam locomotive on English railways is limited by the load gauge in the limited by the size of the driving wheel. The gear wheel itself must be 14 inches smaller in diameter than the diameter of the driving wheel on the tread, in order to give the necessary clearance between the gear case and rail level. If the diameter of the pinion is 10 inches, and to secure low maintenance it should not be less than 10 inches for the size of the motor likely to

be used in main-line locomotive practice, the clearance between the bottom of the gear wheel and rail level must be 7 inches as a minimum, hence for a 42-inch wheel the lowest gear ratio possible is 2·8/1. By increasing the wheel diameter a large increase in nominal gear ratio and a considerable increase in effective gear ratio are obtainable. The limiting feature is the peripheral speed on the pitch line. The curve in Fig. 8 shows the effect on tractive effort or effective gear ratio of increasing the wheel diameter from 40 inches to 70 inches, using a 10-inch pinion. A 4/1 gear ratio is, however, sufficient to give as high a tractive effort as can be utilized with a 58-inch wheel on a locomotive on English railways with a 250-h.p. motor unit.

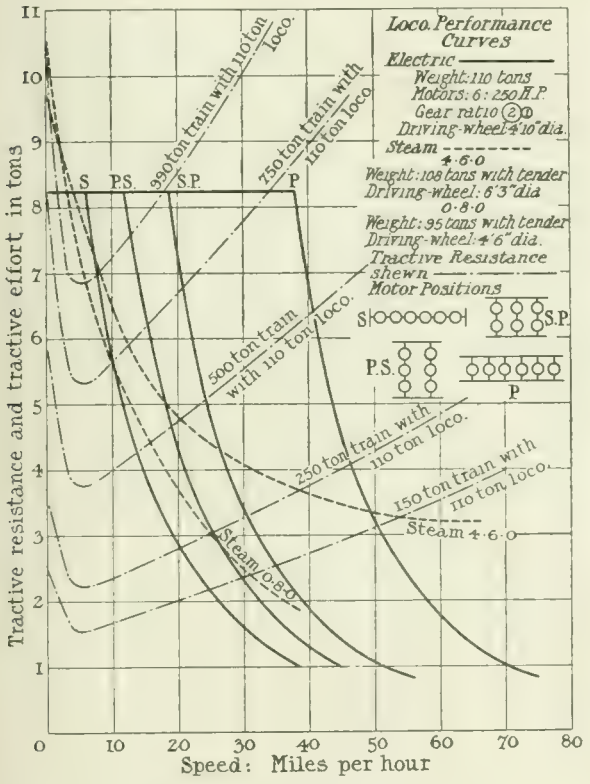

FIG. 3.—Locomotive performance curves.

The usual gear construction, with the gear pressed and keyed on to the axle, gives rise to torsional stresses which invariably sooner or later produce fracture near the wheel seat. The axles of the L. & Y. motor cars equipped with 150-h.p. motors run an average mileage of 170,000 miles before signs of incipient fracture occur. An attempt has been made to improve this by bolting the gear wheel to the road wheel, but the results of this experiment are so far indecisive. Twin gears have been utilized to relieve the axle of these torsional stresses, but, inasmuch as fracture occurs almost invariably between the gear and the adjacent road wheel, it is not clear that this will be effective unless the gears are bolted to the road wheels. The twin gear has the slight disadvantage of reducing the space available for the motor. The inevitable fracture of motor-driven axles after a certain mileage may be due to some extent to the torsional effect arising from the one-sided drive from the motor round curves, the slipping possibly occurring altogether on the wheel furthest from the motor. The failures of axles could probably be completely eliminated by keeping the gear wheel clear of the axle and transmitting the drive directly to twin gears bolted and pressed directly on to the wheel centres.

The curves in Figs. 3 and 5 illustrate the tractive-effort curves of 6-motor, 1,500 rated h.p. locomotives with 4/1 and 2/1 gear ratios, and the train resistance curves of 250 tons (10 coach) and 1,000 tons (50 loaded wagons) trains respectively.

For the sake of uniformity a constant locomotive weight of 110 tons has been assumed in these curves; actually the electric locomotive would be some 20 tons lighter in the case of the 6-motor locomotives, as by

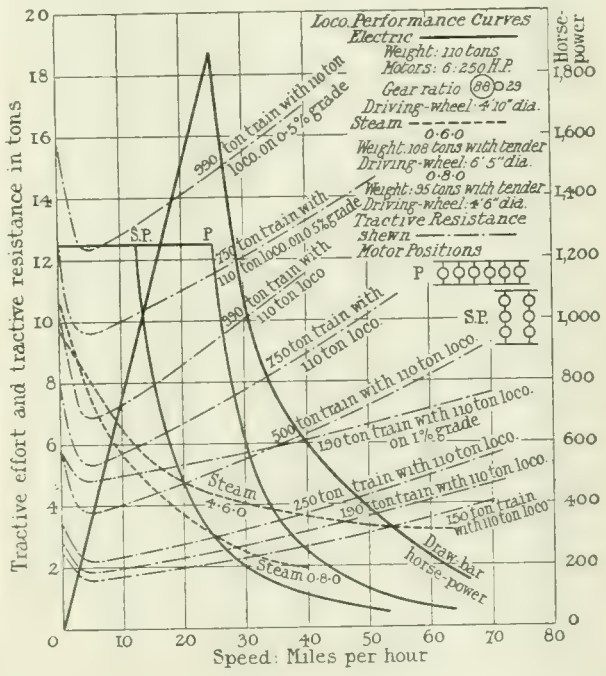
Loco. Performance Curves
Electric
Weight: 110 tons
Motors: 6: 250 H.P.
Gear ratio 29
Driving-wheel: 4'10" dia.
Steam
4-6-0
Weight: 108 tons with tender
Driving-wheel: 6'5" dia.
0-8-0
Weight: 95 tons with tender
Driving-wheel: 4'6" dia.
Tractive Resistance shewn
Motor Positions
S.P.
P
390 ton train with 110 ton loco. on 0·5% grade
750 ton train with 110 ton loco. on 0·5% grade
390 ton train with 110 ton loco.
750 ton train with 110 ton loco.
500 ton train with 110 ton loco.
500 ton train with 110 ton loco. on 1% grade
250 ton train with 110 ton loco.
190 ton train with 110 ton loco.
150 ton train with 110 ton loco.
Steam 4-6-0
Steam 0-8-0
Draw-bar horse-power
Tractive effort and tractive resistance in tons
Horse-power
Speed: Miles per hour

FIG. 4.—Locomotive performance curves.

using the full number of motor combinations and field control the 4-motor equipment will have six running notches, and the 6-motor equipment eight running notches.

The value of utilizing the full number of motor combinations in 4- or 6-motor equipments has not been proved in suburban traction owing to the greater weight and complication involved and the short period of acceleration, but for the locomotive work the acceleration periods are bound to be much longer, and much greater speed variations are required; hence for main-line work the full number of combinations will be found essential, and the difficulty of cost and complexity due to the number of contactors will have to be overcome either by standardization and quantity manufacture or by reversion to the type of direct control

employed on the Liverpool and Southport line. The direct control system has but two disadvantages, its inadaptability to double heading with a single engine crew, and the rather heavier manual work thrown on the driver. It has been shown that a single electric locomotive within the standard loading gauge can handle heavier and faster trains than any steam locomotive that can be designed for British conditions, and that such a locomotive will not exceed 1,500 rated h.p. The direct control seems eminently suited, therefore, to locomotive operation in view of its success on the severest suburban service in the world.

The trend of present-day design indicates that all the requirements of British main-line work could be met by one standard geared motor of 250 h.p., one standard wheel 58 inches in diameter, three standard gear

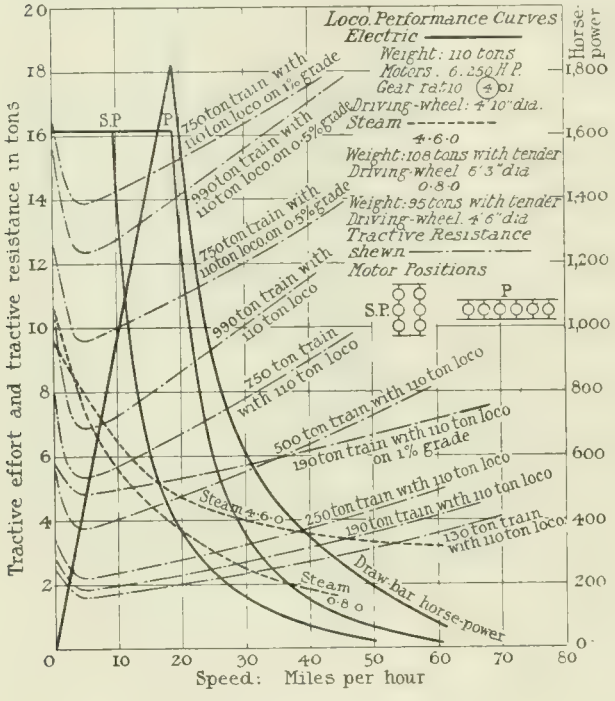
Loco. Performance Curves
Electric
Weight: 110 tons
Motors: 6. 250 H.P.
Gear ratio (4)01
Driving-wheel: 4'10" dia.
Steam
4·6·0
Weight: 108 tons with tender
Driving-wheel 6'3" dia
0·8·0
Weight: 95 tons with tender
Driving-wheel. 4'6" dia
Tractive Resistance shewn
Motor Positions
S.P.
P
750 ton train with 110 ton loco on 1% grade
990 ton train with 110 ton loco on 0·5% grade
750 ton train with 110 ton loco on 0·5% grade
990 ton train with 110 ton loco
750 ton train with 110 ton loco
500 ton train with 110 ton loco
190 ton train with 110 ton loco on 1% grade
Steam 4·6·0
250 ton train with 110 ton loco
190 ton train with 110 ton loco
130 ton train with 110 ton loco
Steam 6·8·0
Draw-bar horse-power
Tractive effort and tractive resistance in tons
Horse-power
Speed: Miles per hour

FIG. 5.—Locomotive performance curves.

ratios 4/1, 3/1, and 2/1, and four standard wheel arrangements 0–8–0, 2–8–2, 0–6+6–0 and 2–6+6–2. The characteristic curves of the locomotives and motors suggested compared with the characteristic curves of typical steam locomotives are shown in Figs. 3, 4, 5, 6 and 7 already referred to above: the efficiency of collector to draw-bar has been taken as 80 per cent.

It is not possible to enter into further details of design, but one or two may be touched upon. Electrical designers delight in small screws which can be, and are, twisted off with a powerful screw-driver or spanner; no set screw or bolt in the electrical portion of the apparatus should be less than $\frac{3}{8}$ inch in diameter, and preferably $\frac{1}{2}$ inch; except for control and lighting cables all conductors should either be bar with bolted joints, all insulation being carried out by mica sleeves and sound mechanical clamps or, where movement is essential, multi-strand cable of extreme flexibility.

It will be seen from these curves that tractive effort and the maximum speeds attained are ample to meet requirements in this country, and that the range of speeds without resistance in circuit is sufficiently great to meet all possible conditions of load and gradient.

OPERATION.

Advantages.—The advantages of the electric locomotive from an engineering point of view are very obvious and may be briefly enumerated:—

(1) Mechanical efficiency is constant for any given tractive effort throughout the life of the locomotive, while that of the steam locomotive diminishes, particu-

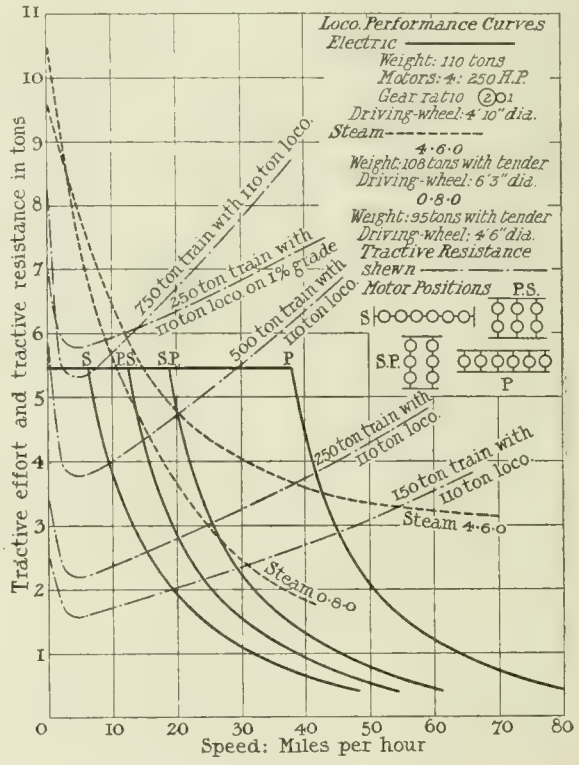

FIG. 6.—Locomotive performance curves.

larly as regards the boiler, in progressively increasing ratio to the time it has been out of the shops.

(2) No coal and no water has to be carried: as the weight of coal, water, tanks and tender represents 20 tons per locomotive on the average, the electric locomotive on this score alone has increased hauling power of two loaded 5-ton wagons, or one bogie coach per train.

(3) The mechanical efficiency is probably higher than that of the steam locomotive, even at full loads. Hobart shows that the efficiency of collector shoe to draw-bar for medium speeds is in the neighbourhood of 80 per cent. This efficiency depends on (*a*) the efficiency of the motor through the gear, and (*b*) the frictional resistance of the locomotive. Actual dynamometer car tests show a mechanical efficiency of the steam locomotive of 72 per cent at 40 m.p.h. for a 2–6–0 type, with a 5 ft. 8 in. wheel, and 82 per cent for a 2–8–0

type at 20 m.p.h. with a 4 ft. 6 in. wheel. Owing to the efficiency characteristic of the series traction motor, trains can be run more efficiently than with a steam locomotive for the efficiency remains practically constant

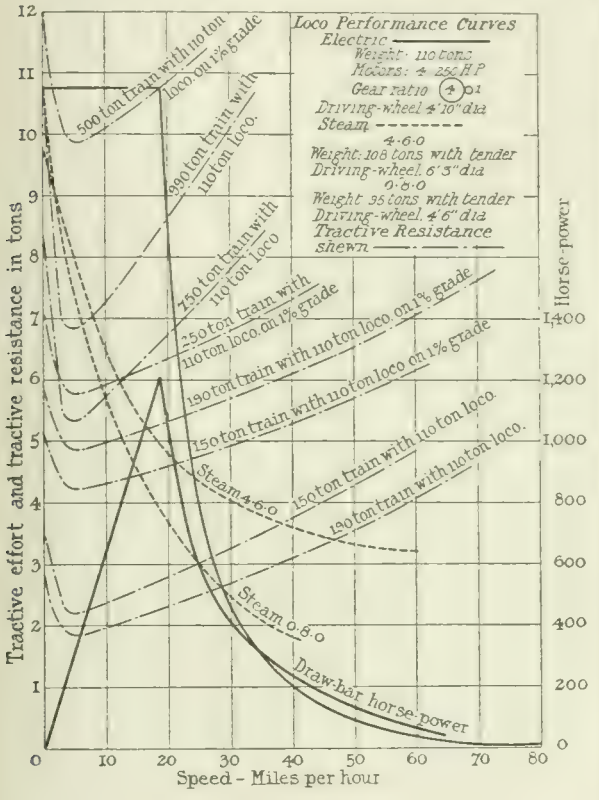
Loco Performance Curves
Electric
Weight: 110 tons
Motors: 4 - 250 HP
Gear ratio 4 to 1
Driving-wheel 4'10" dia
Steam
4-6-0
Weight: 108 tons with tender
Driving-wheel 6'3" dia
0-6-0
Weight 95 tons with tender
Driving-wheel 4'6" dia
Tractive Resistance shewn
500 ton train with 110 ton loco on 1% grade
990 ton train with 110 ton loco.
750 ton train with 110 ton loco
250 ton train with 110 ton loco on 1% grade
190 ton train with 110 ton loco on 1% grade
150 ton train with 110 ton loco.
190 ton train with 110 ton loco.
Steam 4-6-0
150 ton train with 110 ton loco on 1% grade
Steam 0-6-0
Draw-bar horse-power
Tractive effort and tractive resistance in tons
Horse-power
Speed - Miles per hour

FIG. 7.—Locomotive performance curves.

from full load to half load, which is not the case with a reciprocating engine and boiler; hence the electric locomotive can, without loss of efficiency, handle a wider range of loads than the steam locomotive.

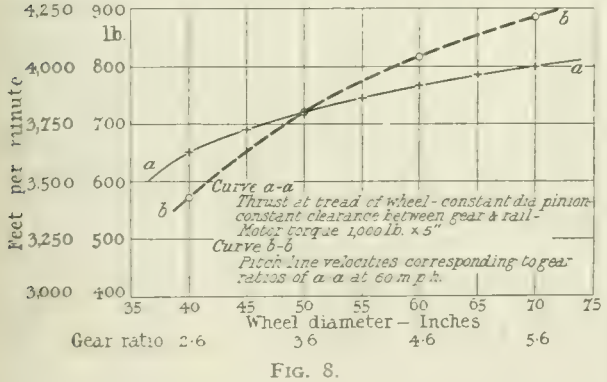
Feet per minute
lb.
Curve a-a
Thrust at tread of wheel - constant dia. pinion constant clearance between gear & rail - Motor torque 1,000 lb. x 5"
Curve b-b
Pitch line velocities corresponding to gear ratios of a-a at 60 m.p.h.
Wheel diameter – Inches
Gear ratio 2·6 3·6 4·6 5·6

FIG. 8.

(4) The tractive effort is more even, the gain in adhesion being of the order of 20 per cent. With a steam locomotive the slipping that occurs may often be noticed to take place for a portion of a revolution only, under certain circumstances. With a steam locomotive, slipping that starts with a full regulator opening results in a momentarily reduced coefficient of friction between rail and wheel and continues until the regulator is closed. With the series motor, on the other hand, the back electromotive force rises, due to the increased speed, and the current and torque are automatically reduced.

(5) The repairs are smaller. An electric locomotive may be expected to run 100,000 miles without failure or renewals of anything except brushes. The average life of the principal parts of the Liverpool and Southport motor cars is given below; the average for locomotives on main-line working, which is much less severe as regards the electrical equipment than a suburban service, might be expected to be double these:—

	Miles
Armature life between re-winds	131,250
Gear life between renewals	250,000
Armature bearing life	73,000
Average life of a steam locomotive boiler to complete renewal	212,000

In connection with repairs it should be borne in mind that the design of standard electric locomotives for main-line work in this country can be commenced on the basis of a wealth of experience gained in the much severer service of high-speed electric traction. To illustrate the probable relative cost of repairs of steam locomotives as compared with electric it may be mentioned that in the early days of the Liverpool and Southport electrification it was necessary for a short time to run steam trains to the electric schedule. The coal consumption was 80 lb. per mile for accelerated express trains, and 100 lb. per mile for accelerated stopping trains, compared with 51 lb. per mile for the electric trains at the power station. The locomotives were 2–6–2 saturated-steam type, and the power station plant consisted of reciprocating engines. With specially designed superheater steam locomotives, the locomotive coal consumption might have been reduced probably by 20 per cent to 80 lb. per mile, but a modern turbine plant would have reduced the power station coal consumption to 25 lb. per mile, or less than one-third the coal consumption of the locomotive. It is a fair assumption and borne out in practice that the boiler repairs represent 50 per cent of the total cost of repairs of the steam locomotive and are proportionate to the coal consumption. It is stated by McHenry that the actual coal economy effected by electrification on the New York, New Haven and Hartford Railroad was: Passenger services 50 per cent, freight services 60 per cent, shunting services 66 per cent, while the cost of repairs per engine-mile was expected to be less than half. It appears to the author a not unfair assumption that the substitution of the electric for the steam locomotive would effect an economy of not less than 33 per cent in repairs, and 50 per cent in coal consumption. It should be further taken into account that the repairs to electric locomotives do not in general demand any complete dismantling of the locomotive; the repairs are confined to the periodical removal of the wheels for turning, and the motor armatures for re-winding at much longer intervals.

(6) No washing-out of boiler or removal of ashes required.

(7) Less cleaning required.

(8) Less lubricant required. Actual consumptions over long periods are 0·01975 pint per mile for the Liverpool and Southport and Manchester and Bury motor cars of 800 h.p. rated motor capacity as against 0·0726 pint per mile, as an average figure for steam locomotives.

(9) No detentions due to lack of steam.

(10) Less failures, causing interruption of traffic.

(11) More rapid shunting movements.

(12) Regenerative braking possible.

(13) No turn-tables required.

(14) Cheap and efficient supply of electricity for lighting, cranes, etc.

(15) Roads now used by engines going to and from shed to turn, for water or for coal, would be available

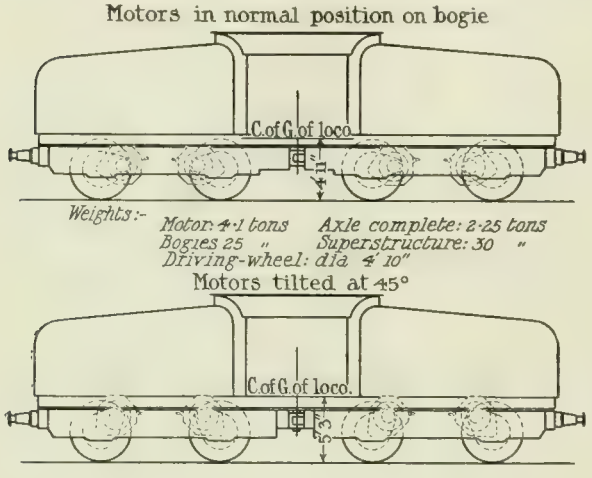

FIG. 9.—Effect of tilting motors through 45° on height of centre of gravity of vehicle.

for traffic purposes, and engine mileage for this purpose would be eliminated.

(16) More than half the wagons now used for locomotive coal would be freed for other traffic. This would amount to 830 wagons, equal to 2·4 per cent of the whole wagon stock on the Lancashire and Yorkshire line.

(17) Owing to the more continuous use made of the locomotives, and the consequent smaller number, at least 33 per cent of the locomotive sheds and shed yards could be devoted to other purposes.

(18) The electric locomotive within the standard minimum load gauge of the British Isles can be made 50 per cent more powerful than any existing steam locomotive. Any necessity for strengthening bridges to meet the needs of more powerful locomotives could be obviated by a general electrification.

It should be noted that one of the serious problems in connection with increasing of the load gauge in the British Isles to the Continental load gauge would be the consequent necessity for strengthening the bridges and viaducts to meet the more powerful steam locomotives which would then come into use.

(19) Double heading with a single train crew is possible, if required and if multiple-unit control is used.

(20) Automatic increase of torque with reduction in speed enables tonnage loading to be maintained over variable grades without reduction in schedule.

(21) Elimination of the smoke nuisance.

Disadvantages.—These are :—

(1) Liability of hold-up of all trains due to failure of current supply.

(2) Difficulty of heating existing carriage stock.

(3) Difficulty of controlling acceleration in shunting operations.

(4) Difficulties incidental to electric operation arising from presence of a trolley wire or third rail and the collection therefrom.

(5) Difficulty in arranging locomotive and rolling stock workings to give the locomotives the continuous use of which they are capable.

(6) Assumed higher cost per ton of an electric locomotive as compared with a steam locomotive of the same maximum horse-power.

The author only proposes to deal with three of these points in the scope of this paper.

Difficulty (3) can be overcome by the use of all four or all six motors in series and the use of liberally proportioned resistances and by field control; the alternating-current motor has an advantage in this respect in a greater number of running speeds being available.

In regard to (4), the current must be collected from either a trolley wire or a third rail; the comparative merits of these types of supply are well known. Briefly, the trolley is inflexible in regard to extensions, and difficult to install or repair without interruption to traffic, and is a serious obstruction to the breakdown crane.

The third rail is an obstruction on the track and therefore objectionable inherently: it is an obstruction to the ordinary maintenance of the track and intolerable in sidings where much shunting is done; in these latter places, however, the objection can be much modified by flooring the spaces between the tracks with wood at a level only an inch or two below the level of the top of the third-rail guarding. The probability is that in main line electrifications the third rail will be used where track complications are not great and where little shunting is done; the trolley elsewhere. The locomotive will therefore have to be equipped with both bows and shoes. With locomotive operation of heavy trains, continuity of contact will be essential; at junctions, gaps which the shoes of the locomotive will not span occur in the third rail; this gives rise to severe jerks on the train. Overhead wires must therefore be installed at these points. The trolley wire where installed must be at least 2 ft. above the loading gauge; the bow must therefore either rise automatically wherever encountered, and fall automatically on leaving it, or, if the bow is permanently up, all points where it might foul the load gauge must be equipped with trolley wires. In this connection much discussion has taken place in regard to standardization of collector voltage and position. In Great Britain to-day there exist two types and three positions of the third rail, three direct-current voltages and one alternating voltage. The

question of the most suitable voltage of supply has been frequently discussed, but remains undecided. The author does not consider that the existence of the comparatively few suburban electrifications at 600 volts or 1,200 volts should militate against the adoption of a standard 1,500 volts. The inclination towards higher voltages mainly arises from three causes: (*a*) the reduction in copper effected, (*b*) the improved commutation with smaller currents, (*c*) the economy arising from concentrating the substation machinery in fewer substations. None of these advantages are of serious moment either practically or financially except where the density of traffic falls considerably below that of any suburban electrification existing to-day in Great Britain. The use of 1,500 volts for electric traction is desirable solely for the sake of future main-line electrification work for reason (*c*); as this field is practically untouched, the first extensive electrification carried out is likely to standardize both voltage and third-rail position. It is, of course, practicable to operate locomotives at two voltages, but the facility is dearly bought as regards first cost and maintenance by the only practical solution of connecting motors permanently in series for the higher voltage running, thus multiplying the number of motors to be maintained and the contactors in connection therewith. The suburban electrifications that exist at 600 volts are almost self-contained as regards both rolling stock and tracks in the few instances; and on the short mileages, where main-line stock utilizes suburban tracks, duplication of the collecting system by putting the higher voltage overhead is preferable to saddling the main-line system with other motors permanently in series and additional contactors. In some few cases half-speed operation of the main-line locomotives would meet all requirements.

The cost of electric locomotives is undoubtedly high, but the author suggests that this high cost is due more to the experimental natures of the designs and the small numbers built to any particular design rather than to any inherent feature of the electric locomotive. The frames, wheels, brake rigging, draw gear and superstructure of an electric locomotive should cost no more than in the case of a steam locomotive. These items represent approximately 60 per cent of the total weight.

The cost of an electric locomotive built in large quantities and to standardized designs should not exceed that of a steam locomotive capable of doing the same work. To-day a 2–8–0 steam locomotive costs approximately £10,000 to £14,000; it is difficult to believe that an electric locomotive of similar draw-bar horse-power would cost any more, for it must be emphasized that any comparison made, to be of value, must be based on draw-bar horse-power.

Financial Aspect.

In dealing with the financial aspect of the substitution of electric for steam locomotives, deductions favourable to electrification have been drawn from general figures applying to the whole of the railways of Great Britain or the United Kingdom. The author suggests that, even as indicating tendencies only, such figures must be taken with caution. The laws defining which streets of a town are worth a tramcar or omnibus route, and which are to be served by horse-drawn or pedestrian transport are similarly applicable to a railway network: there is a certain density of traffic below which an economy will not be obtained sufficient to pay an adequate rate of interest on the capital expenditure in electrifying, nor to provide a sinking and renewal fund. Sufficient experience does not exist to define this limit, but an approximate examination of a particular case will give some indication to be arrived at as to whether the particular section examined will bear electrification or not. To illustrate the point, the case of a railway with one of the most dense traffics in England, as compared with that of the aggregated railways of England and Wales, may be considered.

	1913	
	England and Wales	Lancashire and Yorkshire Railway Company
Route miles	15,655	600
Number of steam locomotives	20,815	1,577
Steam locomotives per route mile	1·33	2·62
Engine-miles per annum	525,804,000	33,536,000
Percentage of shunting miles	18·98	28·16
Engine-miles per route mile per annum	33,586	55,893
Maintenance and renewal of rolling stock, locomotives	£5,453,650	£337,000
Cost per engine-mile	2·49d.	2·41d.
Locomotive running expenses	£15,390,900	£956,000
Cost per engine-mile	7·02d.	6·84d.
Engine-miles per engine per annum	25,260	21,265

These figures, taken from the Railway Returns of 1913, indicate how dense the traffic is on the railway in question as compared with England and Wales generally.

It is obvious that even on the L. & Y. Railway there are many route miles on which the traffic would not warrant electrification; the single-track mileage is 2,224 miles, of which sidings amount to 743 miles, the electrification of 600 route miles would involve, sidings excepted, the electrification of 1,481 miles of track, say 1,600 miles including entrances to sidings. It is interesting to make a rough estimate of the cost of electrifying the whole of this railway on which traffic is so dense. It is a difficult matter to ascertain the exact energy consumption that will be required for the whole of a railway system without obtaining a number of dynamometer car records of typical trains. An approximate estimate may be made on the basis of the tests tabulated in the table on page 866.

The train-miles run over the company's system by the company's engines are divided as shown below, also the total electrical output per annum calculated on an arbitrary basis estimated from the above tests of 12 units per passenger-train-mile, 25 units per goods-train-mile, 8 units per shunting and assistant mile and

steam rail-motor-mile, and 22 units per electric traction-mile.

Class of Train-mile	Miles	Units per Train-mile	Approximate Units per Annum
Coaching	11,247,616	12	135,000,000
Goods	4,993,321	25	125,000,000
Shunting and assistant and steam rail motor	13,355,565	8	107,000,000
Electric traction ..	1,765,879	22	39,000,000
Total	31,362,381	13	406,000,000

Assuming that these units are spread uniformly over 24 hours per day for 338 days per annum (311+27) =8,100 hours. The average load in kilowatts is approximately 50,000 kw. The maximum intensity of traffic in the same time as two with steam. In the particular case in question, the locomotive rolling stock may be classified approximately as follows:—

Passenger	480
Goods	850
Shunting	300

Continuous use could not easily be found for the passenger engines, as the passenger traffic is practically non-existent between 9 p.m. and 7 a.m. It appears probable that, owing to the general slower movement of goods trains, the passenger locomotives could be utilized for certain classes of goods trains using the series and series-parallel combinations only, as can be seen by a comparison of the series-parallel tractive effort curves of the 2–6+6–2 and 2–8–2 locomotives with 2/1 gear ratio in Figs. 3 and 5. A more continuous use could be found for the goods engines, as the goods traffic, though most intense at night, continues throughout the 24 hours. It is doubtful if the number of shunting engines would be reduced, though quicker shunting and fewer service delays would reduce the number to some extent. Assuming reductions of

Type	Weight of Train, tons	Length of Run, miles	Average Speed, Approximate m.p.h.	Units at Draw-bar per Train-mile	Efficiency Collector Shoe Draw-bar, per cent*	Efficiency H.T. Busbars over Collector Shoe*	Units per Train mile at Generating Station
Passenger, steam hauled ..	142	36	55	7	80	80	11‡
Goods, steam hauled ..	801	39	20	23	80	80	36‡
Electric motor cars ..	144	18½	45	7	80	80	11‡
*Butte Anaconda and Pacific goods, steam hauled	1,040 Up grade / 3,550 Down grade	40	20	75	80	80	117
Actual suburban electrification	180	38	30†	14	80	80	22

* HOBART: "Electric Railways," *Proceedings of the Institution of Civil Engineers*, 1916, vol. 201. † Stop every 1·26 miles.
‡ Dynamometer car record reduced to electrical units.

would probably rise to 25 per cent above the average, it being borne in mind that during the hours when passenger traffic is at a maximum, goods traffic is at a minimum.

The maximum one-hour load may be therefore taken at 62,500 kw. Five 12,000-kw. units should carry this load and would allow for peaks of 80,000 kw.

The assumption is further made that 1,100 electric locomotives would replace 1,600 steam locomotives on the individual railway in question as a rough estimate based on various data. The Butte Anaconda and Pacific Railway were able to substitute 17 electric and 4 steam locomotives for 27 steam locomotives, and the schedule was accelerated by 100 per cent and the weight of the trains by 35 per cent; it is believed that the North Eastern Railway have found that six electric locomotives will do the work of 12 steam locomotives. These are, however, special cases of mineral traffic on heavy gradients. J. A. Droege, General Superintendent of the New York, New Haven and Hartford Railroad, states that after electrification it was found that three round freight trips between New York and Bridgeport (Conn.) could be made

25 per cent in the passenger, 40 per cent in the goods and 10 per cent in the shunting engines, the number of electric locomotives required would be 1,140. Looking at the question from another aspect a total of 1,600 engines is required to maintain 1,200 engines steamed daily: 400 being the required number for works and shed repairs, etc. Assuming that the work of 1,200 steam locomotives could be done by 900 electric locomotives and that 200 instead of 400 were required for repairs, etc., for the reasons given in paras. 5, 6, 7 and 15 on pages 863 and 864, then the total number of electric locomotives required would be 1,100.

The capital cost of electrification would then be as follows at pre-war prices.

	£
84,000-kw. generating station at £10 per kw.	840,000
80,000-kw. substation plant at £6 per kw...	480,000
300 miles transmission at £3,000 per mile ..	900,000
*1,600 miles of track at £2,000 per mile ..	3,200,000
1,100 locomotives at £5,000 each	5,500,000
Total	£10,920,000

* Includes overhead equipment in goods yards entrances, and alterations to signalling.

£10,920,000 is not the real capital expenditure, for from this has to be deducted the cost of renewals of the existing steam locomotive stock during the period of years covering the electrification operation, and the sale value of the remainder. Deductions also require to be made for site and traffic values of disused locomotive sheds, turn-tables, and roads freed from traffic for engine purposes. Evaluating the credit for steam locomotive renewals and sales at £2,000,000 and the site values freed at an arbitrary figure of £420,000, the net cost of electrification stands at £8,500,000.

The actual costs of steam operation in 1913, and assumed economy by use of electric locomotives are shown in the following table, liberal percentages being allowed to put the most favourable complexion on the financial results of the proposed change, and making no allowance for increased track maintenance charges.

Actual Locomotive Costs, 1913.

	£	Assumed Percentage Economy	Total Economy, £
Superintendence ..	25,000	Nil	—
Running wages ..	394,000	25	100,000
Fuel	432,000	50	216,000
Water	33,000	Nil	—
Lubricants	13,000	50	6,000
Stores and miscellaneous	33,000	Nil	—
Repairs	316,000	33	105,000
Total	—	—	427,000

The coal used under conditions of electric haulage is that required for 406,000,000 units at 2·0 lb. of coal per unit=363,000 tons of coal, whereas the coal actually used on steam locomotives in 1913=726,512.

If regenerative braking permitting a return of only 15 per cent of the energy to the line was used, the coal consumption would be considerably less than half that under steam-haulage conditions. The Chicago, Milwaukee and St. Paul line, a rather special case owing to long gradients, claim a 35 per cent return to the line.

The economy effected may be looked at in another way; the cost of generating electric power in an 84,000-kw. station would not exceed 0·25 per unit generated at 1913 prices, considering the high load factor which would be obtained, and the comparatively small and simple distribution system and the homogeneity of the equipment. The total cost of current would then be £423,000 per annum. This is nearly equivalent to the cost of coal with steam traction; the economy then possible is limited to that which can be effected in running wages and repairs, approximately £200,000 per annum.

It will be seen that the economy effected could not offer a return of more than 5 per cent on the capital expenditure. The figures are applicable to the present day if approximately doubled, and the probability is that the return would be less than 3 per cent.

The salient points arising from these rough estimates, which though based mainly on arbitrary assumptions are probably substantially accurate, are the very large proportions of the total capital expenditure debited to the transmission (11·2 per cent), track (40 per cent), and locomotives (25 per cent), and the very clear indication given of the substantially greater return on capital expenditure which would be obtained by retaining steam operation by those services on which the expenditure per mile for fuel and repairs was low.

It is evident, therefore, that if electrification is to be regarded from the point of view of economy in operation denser traffic areas must be sought than are offered by the whole Lancashire and Yorkshire system, dense as is its traffic compared with the average for England and Wales. On the other side of the scale are the improved facilities offered for the movement of traffic and the possibilities of increased revenue. Experience in the U.S.A. and elsewhere has shown, as for instance on the Butte and Anaconda Railway, that electrification will enable substantial increases in schedule speed and train weight to be effected. These increases would probably result in increased and not decreased expenditure per train and per ton-mile, while the increased revenue is a matter for speculation, because the traffic problem is not merely a problem of moving trains faster, at least as far as goods traffic is concerned.

Given sound engineering design the ratio:

$$\frac{\text{Cost of current-producing plant}}{\text{Cost of track equipment and locomotives}}$$

will give a general indication of the probable commercial success of an electrification scheme. For a typical suburban electrification this ratio is approximately 1; in the case under consideration it is approximately 0·25.

It is evident that, in the case under consideration, if the track to be electrified could be reduced by one-half, while the number of locomotives required is only reduced by one-third, then the total capital expenditure would be reduced to £5,500,000 while the economies effected might only be reduced by one-fifth. The return on the capital expenditure would then become approximately 8 per cent for a ratio of approximately 0·4. Immediate electrifications will be limited to densely trafficked sections of the main line when a maximum continuous use can be obtained from both locomotives and track equipment, and where the expenditure on these items is such that the expenditure ratio is 0·5 or more.

In conclusion, the continuous use of both the locomotives and track is therefore the key to the whole problem of main-line electrification in its financial aspect, and this is rather a railway than an electrical or mechanical engineering problem. It is for the engineer to design an electric locomotive sufficiently flexible to work efficiently either goods or passenger trains; those responsible for traffic operation have the equally difficult task of arranging the workings for the

train services, which must suit the public convenience, in such a way as to secure the continuous use of the tractors, which is made practicable by electric traction; not the least difficult point to be dealt with in investigating this is the arrangement of the change-over from electric to steam haulage at the terminals of the electrification. It is also for the traffic department to determine whether greater loads hauled and the higher average speeds and more rapid clearing of the block sections will enable their work to be done so much more efficiently and economically as to compensate for the increased costs of locomotive operation consequent on such increased loading and acceleration.

The author has endeavoured in a broad way to draw the conclusion, confirmed by what has been done on the Chicago, Milwaukee and St. Paul and on the Italian and Swiss Railways, that sufficient data and experience exist to enable the engineer to design electric locomotives of the type required, and to predetermine with accuracy the capital expenditure and operating costs, but that the determination of the most suitable sections to electrify is essentially a traffic problem. He ventures to join his predecessors in papers dealing with this particular field of traction in the plea for the immediate appointment of Committees to deal with the standardization of third-rail position and voltage, motors, gearing, contactors, and locomotives. It has been and will be urged that such standardization is a bar to progress, but standardization carried out with due regard to future progress, and in which due weight is given to the practical knowledge of the operating staff of the railways, will be no bar. It will be a misfortune if, from apathy or any other cause, the introduction of the new form of traction on railways is allowed to give birth to the multiplicity and variation of types and details, mostly unimportant in their bearing on efficiency, which characterize British steam-locomotive practice of the present day.

APPENDIX A.

The following Table gives the cost of Repairs, Wages, Repairs Materials, Stores, Inspection, General Maintenance of all Electrical Equipment and Motor-bogies, Electrical Equipment of Trailers, but exclusive of trailers and the coach bodies of the motor-cars, i.e. it is a true representation of the cost of maintenance of the motive power portion of Electric Rolling Stock :—

Half-year ending—	No. of Motor-cars at end of Half-year	No. of Motors	Wages		Materials		Wages and Materials			Total Cost per Motor, 125 or 150 h.p.	Oil All Classes per 1,000 Motor-miles	Average No. of Miles per Motor-car per Annum	
			Total	Per Motor-mile	Total	Per Motor-mile	Total	Per Motor-car	Per Motor-mile				
			£	d.	£	d.	£	£	d.	£	galls.	miles	
June 1906 ..	51	178	3,458	0·173	3,016	0·151	6,474	127	0·324	36·4	0·605	49,456	—
Dec. 1906 ..	52	180	4,885	0·218	4,056	0·208	9,541	184	0·426	53·0	0·504	56,460	—
June 1907 ..	52	180	4,902	0·223	5,097	0·231	9,999	192	0·454	55·5	0·514	57,042	—
Dec. 1907 ..	60	212	5,395	0·231	4,239	0·182	9,634	161	0·413	45·4	0·605	52,840	—
June 1908 ..	64	228	5,108	0·226	4,184	0·183	9,352	146	0·409	41·0	0·730	48,114	—
Dec. 1908 ..	64	228	4,362	0·191	3,119	0·136	7,481	117	0·327	32·8	0·777	48,598	—
June 1909 ..	64	228	5,141	0·243	2,470	0·117	7,611	119	0·360	33·4	0·736	—	—
Dec. 1909 ..	64	228	4,689	0·202	2,503	0·108	7,192	112	0·310	31·5	0·753	46,120	—
June 1910 ..	64	228	4,300	0·190	2,293	0·101	6,593	103	0·291	28·9	0·712	—	—
Dec. 1910 ..	64	228	4,864	0·203	3,389	0·141	8,253	129	0·344	36·2	0·589	47,763	—
June 1911 ..	64	228	4,394	0·190	3,524	0·153	7,918	123	0·344	34·7	0·732	—	—
Dec. 1911 ..	64	228	4,086	0·166	4,025	0·164	8,111	126	0·330	35·5	0·695	48,528	—
June 1912 ..	64	228	4,071	0·173	3,410	0·145	7,481	117	0·318	32·8	0·697	—	—
Dec. 1912 ..	66	236	4,746	0·189	3,195	0·127	7,941	120	0·316	33·6	0·689	48,861	—
June 1913 ..	70	244	7,237	0·285	5,578	0·220	12,815	183	0·505	52·5	0·673	—	—
Dec. 1913 ..	72	244	7,398	0·258	7,090	0·247	14,488	201	0·505	59·4	0·705	48,949	—
June 1914 ..	72	244	6,770	0·248	7,368	0·270	16,421 †	228	0·601	67·3	0·766	—	2,283
Dec. 1914 ..	78	268	7,177	0·256	5,764	0·205	14,058 †	180	0·501	52·5	0·651	46,347	1,117
June 1915 ..	78	268	*	—	—	—	—	—	—	—	0·726	—	—
Dec. 1915 ..	78	268	—	—	—	—	—	—	—	—	0·793	40,760	—
June 1916 ..	78	268	—	—	—	—	—	—	—	—	0·787	—	—
Dec. 1916 ..	78	268	—	—	—	—	—	—	—	—	0·828	38,895	—
June 1917 ..	78	268	—	—	—	—	—	—	—	—	0·852	—	—
Dec. 1917 ..	78	268	—	—	—	—	—	—	—	—	0·892	38,323	—
June 1918 ..	78	268	—	—	—	—	—	—	—	—	0·925	—	—
Dec. 1918 ..	78	268	—	—	—	—	—	—	—	—	0·807	37,663	—

* These figures are not carried forward owing to the fact that the conditions arising out of the War made them useless for comparative purposes.
† Includes cabling by C. and W. Department.

APPENDIX B.—Mileage between Overhaul.

Half-year ending—	Standard Bogies	Wheels between turning up of Tyres, 150 h.p.	150-h.p. Armature	All Classes of Armature	Life of Brushes	Life of Shoes	Life of Brake Blocks	Wheels between turning up of Tyres	
								125 h.p.	250 h.p.
	Miles	Miles	Miles	Miles	Miles	Miles	Miles	Miles	Miles
June 1906	17,750	—	—	—	11,000	—	1,083	—	—
Dec. 1906	28,800	39,000	124,000	44,000	11,680	112,500	1,784	—	—
June 1907	32,700	38,000	115,000	41,700	12,640	127,300	1,915	—	—
Dec. 1907	32,600	49,400	87,300	49,000	15,550	116,000	2,150	—	—
June 1908	32,800	42,300	128,000	63,000	13,300	78,500	2,320	—	—
Dec. 1908	28,500	30,300	171,030	87,100	10,900	102,000	2,680	—	—
June 1909	25,260	27,420	170,850	83,930	11,180	61,600	3,251	—	—
Dec. 1909	30,150	30,000	278,270	55,780	14,800	131,810	3,587	—	—
June 1910	28,650	30,400	237,440	65,730	13,510	83,100	2,763	—	—
Dec. 1910	27,010	29,330	256,610	63,890	11,430	85,530	2,512	—	—
June 1911	29,632	31,656	283,148	55,705	12,134	55,398	2,055	—	—
Dec. 1911	31,824	35,210	293,490	129,374	14,889	89,539	3,059	63,549	—
June 1912	32,072	33,321	285,088	81,148	18,099	122,181	2,929	78,194	—
Dec. 1912	48,124	41,879	189,176	66,183	17,049	119,263	2,930	59,613	—
June 1913	59,430	42,972	98,007	66,043	15,113	103,452	2,836	122,394	—
Dec. 1913	41,200	34,144	137,335	64,122	14,288	93,638	3,328	28,531	123,220
June 1914	34,287	32,961	126,934	52,263	10,576	67,033	2,663	30,590	22,206
Dec. 1914	41,834	34,507	142,042	62,092	8,185	71,021	2,688	61,113	48,852
June 1915	45,873	36,816	148,207	63,722	9,164	56,117	2,340	51,512	18,742
Dec. 1915	34,008	29,203	149,258	56,954	11,067	94,268	2,450	36,744	15,500
June 1916	28,770	30,078	132,345	67,520	12,420	99,883	3,431	41,505	16,116
Dec. 1916	30,045	29,547	144,542	71,246	11,678	172,518	3,683	24,724	7,806
June 1917	27,115	24,813	95,644	64,382	10,364	70,139	3,394	75,723	44,889
Dec. 1917	29,830	30,526	116,678	70,024	12,108	114,142	2,768	56,772	15,280
June 1918	28,534	24,656	95,832	57,323	12,500	74,692	2,740	25,038	44,287
Dec. 1918	28,860	27,342	140,403	91,188	13,686	73,168	2,850	96,699	16,865

The original diameter of the commutators was 17¼ inches, and the tread wear is approximately 0·175 inch per annum.
These commutators can be worn down to 15 inches, so that their total life is about 14 years; in fact a large number of the commutators originally fitted are still running.

APPENDIX C.—Overhaul Periods and Mileages between Shed Overhauls of Electric Stock, Manchester and Bury Electrification.

	At the Present Time	
	Period	Mileage
Bogie framework	6 months	25,000
Wheels	6 months	25,000
Wheels axle bearing	6 months	25,000
Motors main	6 months	25,000
Motors bearing	6 months	25,000
Rotary transformer	6 months	25,000
Pump motor	12 months	50,000
Pump exhauster	12 months	50,000
Main knife switch	Monthly	4,000
Main circuit breaker (overhaul)	Weekly	1,000
Main circuit breaker (examine)	Twice a week	500
Main contactors (overhaul)	Weekly	1,000
Main contactors (examine)	Twice a week	500
Main plugs and sockets	Fortnightly	2,000
Rotary transformer switchgear (overhaul)	Weekly	1,000
Rotary transformer switchgear (examine)	Twice a week	500
Pump motor switchgear (overhaul)	Weekly	1,000
Pump motor switchgear (examine)	Twice a week	500
Brushgear main motor	Twice a week	500
Brushgear rotary transformer	Twice a week	500
Pump motor	Twice a week	500
Shoes and connections	Weekly	1,000
Brakes, pit	Twice a week	500
Oiling, axles	Fortnightly	2,000
Oiling, armatures	Weekly	1,000
Oiling, axle box slides	Weekly	1,000
Oiling rotaries, pump motors, gears	Monthly	4,000
Oiling pump exhauster	Weekly	1,000

CONTRACT PRICES.

By Captain W. P. Digby, R.E. (T.), Member.

(*Extracts from a paper, first received* 3 *December*, 1917, *and in final form* 22 *February*, 1918, *and read before the* North-Western Centre, 9 *April*, 1918.)

Preliminary Note.

Very much of the paper in the form in which it was discussed before the North-Western Centre, at Manchester, was more pertinent to its then title of "Contract Prices during Demobilization." A large part of the contents, which were only of momentary interest, have therefore been deleted. Shortage of paper prevented its publication during 1918 and 1919, and it has therefore been felt that reference to prices, of interest at the time to the statistician, has only a historical value. The present synopsis therefore deals with matters of present and future moment.

The author urges that consideration should be given to some of the factors governing the contract prices for home and foreign markets for electrical, and indeed all general engineering, manufactures, and suggests the provision of machinery calculated to assist in the regulation of these.

It is advisable to define initially some of the related factors which can only be briefly alluded to, and to describe the sense in which certain terms are used.

Of the related factors, that of the mechanism by which wages rates (for skilled and unskilled alike) will be fixed will not be discussed. The author assumes that such mechanism will be existent, and further assumes that the index-numbers for weekly rates of wages for specified trades in the engineering industry will be as readily available as, say, the annual costs per unit generated in certain big power stations. For a definition of index-numbers, that given by Mr. R. H. Hooker in a paper read before the Royal Statistical Society * is employed.

Mr. Hooker describes the use of a system of index-numbers in the following terms:—

"The process consists in accepting the price of a single date, or of a series of years, as a standard, and representing this price by the figure 100. The price at any other time (be it that of a given day, or an average of monthly or yearly prices) is then expressed as a percentage of the standard value; and this resultant percentage is called the index-number of the commodity at the date or period to which it refers. Similar percentages are formed for various other articles; and the addition of the index-numbers of all articles at a given period (usually divided by the number of articles taken, so as to express the result also as a percentage) gives what may be called a total index-number. The changes from year to year, or from month to month, of the latter figure then form a very useful measure of the change in value of commodities as a whole.

"The above represents the simplest form of index-number, and it is quite arguable that, as a measure of the change of *prices*, it is the most satisfactory. But as a measure of the change in value of the expenditure of a household, it perhaps affords a less satisfactory guide; inasmuch as it takes no account of the relative importance of the commodities which the householder purchases. In forming index-numbers, therefore, which aim more especially at measuring the effect of a change in prices upon a purchaser's purse, it is customary to make some allowances for the fact that a much greater quantity of certain articles is bought than of others; in other words, the individual index-numbers are weighted before being added to make up the grand total."

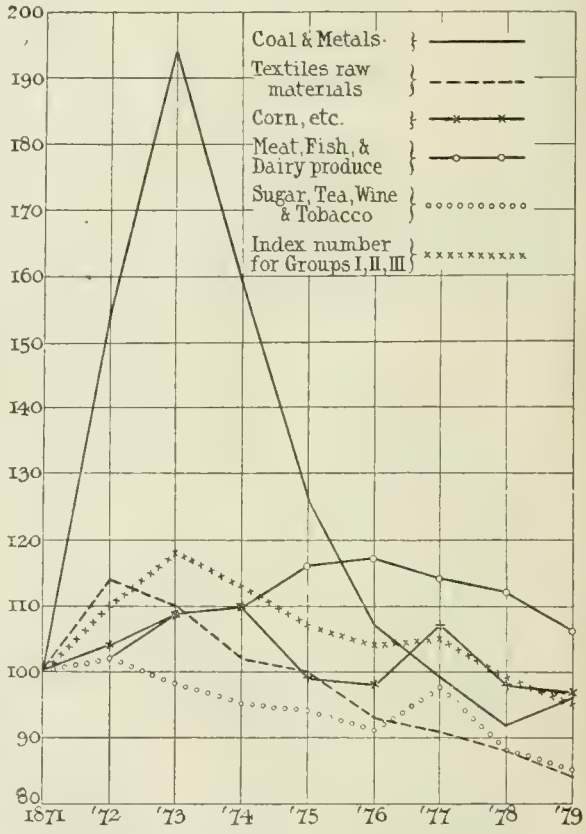

Fig. 1.—Groups of selected articles—United Kingdom.

* *Journal of the Royal Statistical Society*, vol. 75, part 1, pp. 1–50.

Two statistical periods are used as illustrations. The first period calling for consideration is that of the Franco-Prussian War. Like all modern arts, that of the statistician tends yearly to greater amplification and greater detail. In comparison with the mass of data available to-day, our records of four and five decades ago are scanty. We do know that in this country the period from 1872 to 1875 was marked by all the features of a boom period, rising rates of wages and cost of food-stuffs, together with an artificial inflation of prices. In quoting a few of the available figures of this period (see Table 1), the author, while pointing out that war was declared in the late summer of 1870 and peace signed at Versailles in the spring of 1871, thinks that for purposes of illustration the period from 1870 to 1879 should be taken. In some cases a few statistics anterior to 1871 will be quoted, but so far as the United Kingdom is concerned, these will generally be mean prices, not the weighted figures of the Board of Trade index-numbers which are only available from 1871.

Of course the high prices of 1873 must not be claimed as solely due to the effects of the Franco-Prussian War. We have to distinguish between fluctuations due to normal and abnormal causes; the coincidence of both the normal and the abnormal must be here acknowledged. Under the many contributory causes to be grouped as normal we must to-day include labour disputes, effects due to climatic conditions, to say nothing of the progress of bulk production or even the speculative cornering of commodities. As an instance of the fluctuation due to the normal, we may instance the change between 1890 and 1896, when the index-number for all commodities fell from 82·8 to 69·8, and the coal and metals index-number falling from 113·6 to 83·8.

Taking next the average prices for a few commodities from 1869 to 1879, we have the record given in Table 2.

Statistics of foreign countries are somewhat sparse and disconnected, but a selection from those most readily available may be cited.

TABLE 1.

Year	Groups of Selected Articles—United Kingdom					Total of Group III	Index-number for all Articles enumerated in Groups I, II, III
	I	II	III. Food and Drink				
	Coal and Metals	Textiles, Raw Materials	A Corn, etc.	B Meat, Fish, and Dairy Produce	C Sugar, Tea, Wine, Tobacco		
1871	100·0	100·0	100·0	100·0	100·0	100·0	100·0
1872	154·1	114·0	104·0	102·0	102·0	102·7	110·6
1873	194·8	110·2	109·7	109·3	98·1	108·2	118·8
1874	158·8	102·6	110·8	110·1	94·9	108·6	113·6
1875	126·8	100·6	99·9	116·6	93·9	107·3	107·8
1876	107·2	93·6	98·7	117·2	90·7	106·8	104·2
1877	99·9	91·7	107·9	114·9	96·9	110·3	105·3
1878	92·9	88·5	98·9	112·2	88·4	104·2	99·3
1879	86·8	84·1	97·4	106·7	85·2	100·8	94·9

TABLE 2.

Year	Value per Ton of Coal shipped at Newcastle	Mean Selling Price No. 3 Cleveland Pig Iron per Ton at the Works	Mean Value per Ton f.o.b. of Bar, Angle, Bolt, and Rod Iron
	s. d.	s. d.	£
1869	9 0	43 10	7·52
1870	9 0	46 11	8·14
1871	9 0	47 2	8·37
1872	14 5	65 4	11 58
1873	20 5	98 5	13·09
1874	16 11	70 1	11·80
1875	13 2	53 4	9 87
1876	10 9	46 7	8·53
1877	9 9	42 0	7·77
1878	8 7	38 10	7·14
1879	7 9	34 11	6·61

TABLE 3

Price of Wheat.

Year	France	Prussia
	s. d.	s. d.
1869	47 4	42 3
1870	—	44 5
1871	59 8	51 0
1872	53 11	52 8
1873	59 7	57 6
1874	58 5	52 3
1875	45 0	42 8
1876	47 11	45 9
1877	54 7	50 1
1878	49 5	44 0

The official average prices of wheat in France and Prussia during the war period form an interesting example of the time taken for prices to readjust themselves. In this case actual official average figures are quoted and not index-numbers (see Table 3).

During this period there was no relative change of import duties in either country—the bad harvest in 1876 was responsible for the high price of 1877.

Remote though the American Continent was in this period, the average wages rates in the building, metal, stone and cotton trades showed somewhat similar changes to those in France, Germany, and Belgium. The index-number 100 equals the average money rate of wages in each country in 1900:—

TABLE 4.

Wages in certain Skilled Trades in U.S.A.

Year	Average Values expressed as Percentage of Wages in 1900
1869	97·4
1870	97·5
1871	98·4
1872	99·8
1873	100·5
1874	97·1
1875	95·2
1876	91·7
1877	87·1
1878	85·7

TABLE 5.

Wages of French Coal-miners and in Krupp's Foundries.

Year	French Coal-miners' Average Values expressed as Percentage of Wages in 1900	Workmen in Krupp's Foundries. Average Values expressed as Percentage of Wages in 1900
1869	63	60
1870	66	64
1871	66	63
1872	73	71
1873	76	78
1874	79	81
1875	79	81
1876	70	76
1877	73	70
1878	73	67

The general conclusions to be drawn from the typical figures quoted are that:

(1) Food-stuffs, taking wheat as the key, did not revert to their pre-war value until four years after the close of hostilities;

(2) That wages in neutral countries like the United States and Belgium took respectively three and seven years to revert to their old money value;

TABLE 6.

Wages of Belgian Iron-workers.

Year	Belgian Iron workers' Wages. Average Values expressed as a percentage of Wages in 1900
1869	89
1870	89
1871	92
1872	91
1873	111
1874	103
1875	107
1876	98
1877	91
1878	91

(3) That taking the two cases given of belligerent countries, the wages in the defeated country remained until 1876 below those in the victorious country, in neither case reverting to their old value in seven years;

(4) That in the four typical cases given, wages rose in both belligerent and neutral countries after the close of hostilities, due in part to high food prices, and in part to the synchronizing of a period of good trade with the demands to make good much of the material destroyed in the war or diverted to other uses.

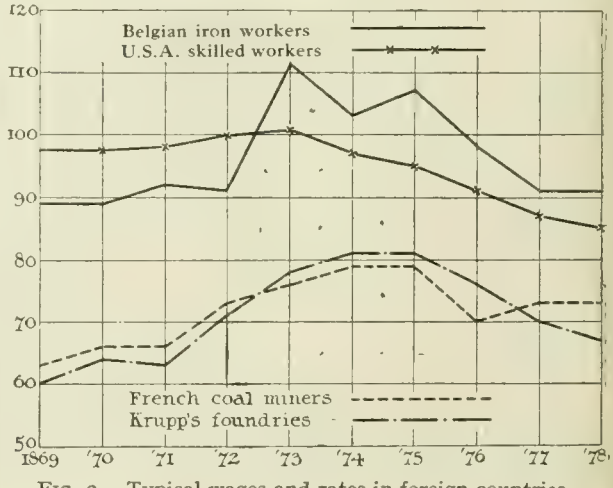

FIG. 2.—Typical wages and rates in foreign countries, 1869–1878.

The second of the three periods from 1890 to 1909—the period analysed by Mr. Hooker in his paper—is only cited as instancing the fact that under pre-war conditions the prices of certain of the most widely used

of the raw materials of the engineering industry were subject to much greater variations in price than were the prices of food-stuffs. This is really a surprising tribute to the adequacy and efficiency of the supply and transport systems of the world, no less than to the successful efforts which were opening up sources of food-stuffs at a rate almost commensurate with the growth of population in the food-importing as distinguished from that in the food-exporting groups of communities.

Figs. 3 to 6 reproduce the figures given in Mr. Hooker's paper, upon which contribution has already been levied.

Fig. 3 compares the variations in the index-numbers of food on the basis of the prices prevailing between 1890 and 1899 in the United Kingdom (Board of Trade figures), United States (Bureau of Labour figures), and Germany (Mr. Hooker's computation).

Fig. 4 treats similarly the variations in the index-numbers of general materials other than food. From the first of these, one notes that while during the late years food prices in the United Kingdom rose perceptibly, they did not exceed the high prices of 1891, when the index-number touched 112 as the result mainly of high prices for cereals. The rate of increase

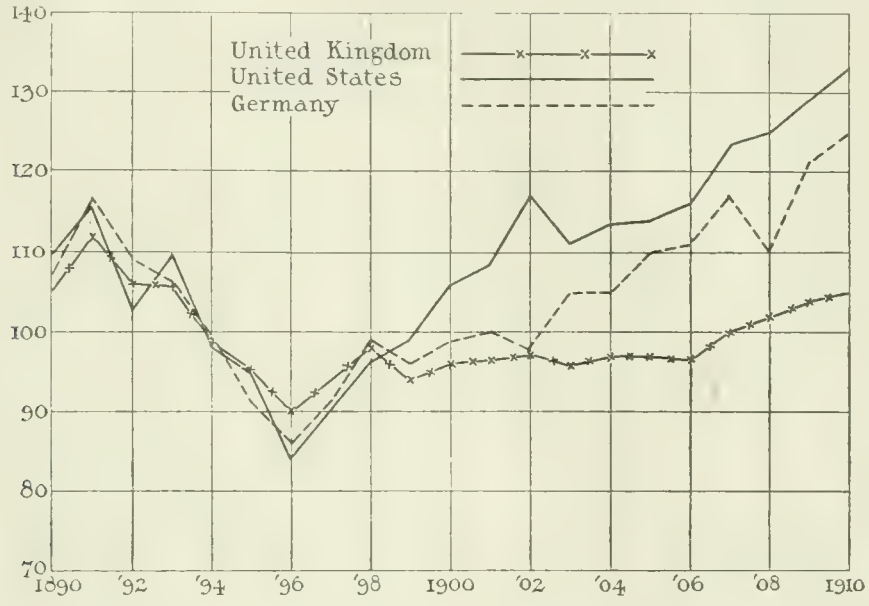

Fig. 3.—Food index-numbers.

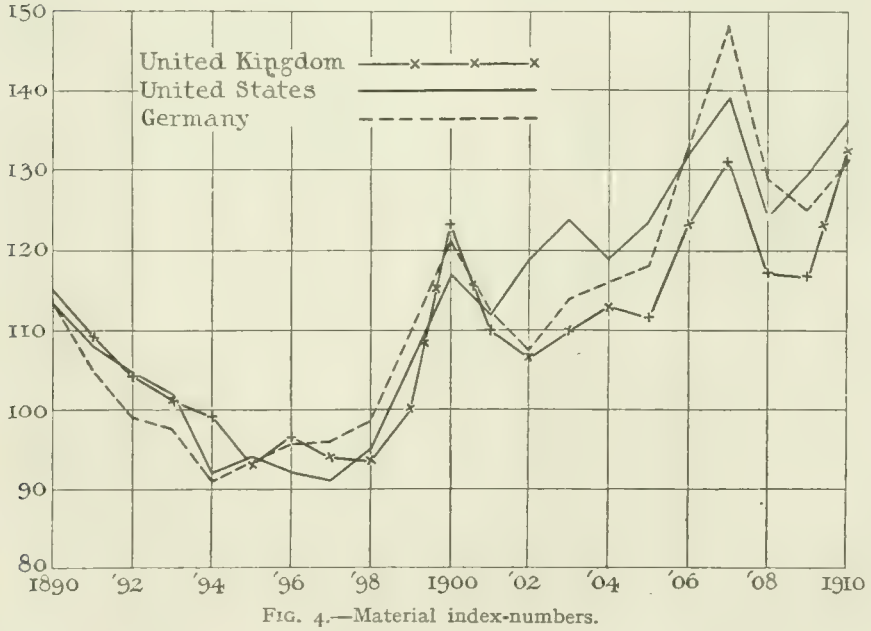

Fig. 4.—Material index-numbers.

in food prices in the United States and in Germany was considerably higher than in this country. As regards general materials, these moved in very much closer sympathy in all three countries. Forces raising prices of food-stuffs in America and Germany were largely due in the one case to a country ceasing to be food exporting, and in the other case to a country becoming to an increasing degree a food-importing country.

Figs. 5 and 6 set out the fluctuations in regard to the United Kingdom alone for the four common engineering materials of coal (Wallsend, delivered London, not perhaps a very good criterion), Cleveland pig iron, tin and copper. In the course of 20 years we thus had pig iron varying between the relative value of 84 in 1893 and 134 in 1907, copper between 80 in 1894 and 165·6 in 1900, and tin between 74 in 1896 and 223 in 1906. These, it must be remembered, too, are mean relative prices for the year, not the extreme fluctuations due to a temporary depletion of stocks.

While the prices of commodities fluctuate in this serious but inevitable manner, their inter-relation and effect on industry can never be a constant one. High fuel prices are an incentive to fuel-saving; high prices

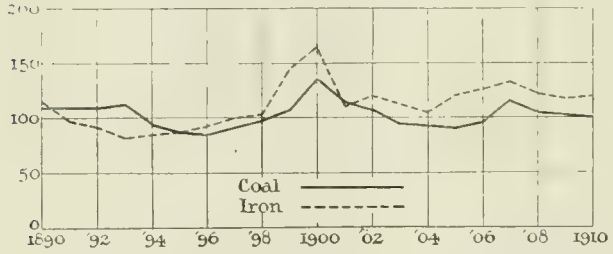

FIG. 5.—Index-numbers for the prices of coal and iron in the United Kingdom, 1890–1910.

for metals both serve to replace a lavish and rule-of-thumb use of the metal by a scientific one, and also, other conditions being normal, occasion a glut through over-production accompanied by the opening of new mines. Low metal prices permit the use of metal for fresh purposes, while closing down unproductive mines as a sequence to cheaper production at the large mines.

The engineering manufacturer, moreover, always has his own works in a continuous condition of evolution. Machine tools are speeded up, the time required for machining operations is reduced, repetition work is the rule where possible. When raw materials rise in price this can only be off-set by a cheapening of the labour cost of the finished article, to which end constant effort is devoted. At the same time the rise in rents, altered standards of domestic comfort and rises in food prices have all tended to complicate the industrial problem.

The token of exchange has received a fictitious importance; for it has no constant value, and cannot be given such while harvests vary, populations increase, and mineral wealth is continuously being lost through wear and tear or corrosion. That is to say, it could only conceivably have a constant value when production and consumption reach and maintain an absolute equilibrium.

By the use of index-numbers we can compare nominal currency values in different years in terms of their relative food- or commodity-purchasing value, and index-numbers must become a feature of all studies in engineering economics.

But there is also room in engineering for the application of index-numbers to the true interpretation and analysis of activity in a number of directions. Thus, say for steam boilers, if the unit of comparison were the selling price per 1,000 pounds of rated evaporation from and at 212° F., strictly comparable figures could be produced from the index-number of the selling price in any year as contrasted with the respective index-numbers of the materials and labour required. The wages boards in the colliery districts were, even before the war, urged by the colliers' representatives to take into account changes in the food-purchasing value of the pound sterling. If similar boards should ever be established in other industries, those responsible for the presentation of the employer's case should be ready with figures of the burdens laid upon them by the extraneous causes of rises in prices of raw materials, together with figures of the prices at which competing products from other countries are being sold. We must remember that the increased output of new machine tools has on the one hand increased the output of each artisan, but has increased works standing-charges. Parallel with this, selling-prices for some classes of machinery had before the war fallen to a very low point. It is therefore advisable that our commercial analyses should be as full as possible, and full emphasis be laid on the fact that while increased food prices do not inflict the direct hardship upon the manufacturers that they do upon the skilled artisan or unskilled worker, increased prices for materials make his position very difficult and may either render it easy to pay all that labour considers or may consider its due, after the war, nor easy to meet the competition of other countries also bartering manufactured goods for food. It is quite true that, before the war, profits were earned in times of activity because the percentage incidence of establishment charges, together with the increased selling price, then offset the increased price of materials.

We cannot come to any equitable settlement of economic problems so long as the community regards any unit of currency as a fetish of a stable potency, instead of in its correct position as the resultant of a large number of complex forces. A scientific unit of currency based on things definite like a physicist's absolute system of units of measurement is an impossibility. Old civilizations came near to one when they fixed the indemnity or tribute of a conquered province at so many head of cattle or at a definite weight of corn. Gold, or rather the paper credit representing it which our modern civilization has evolved, is a more fluid medium of exchange. We must recognize its essential instability, both in other countries and in our own, if we are to gauge correctly the trends of industrial development and to prepare to meet the immediate future with any confidence.

[Various tables and diagrams relating to the prices of electric motors, switchgear, electric cables, copper, lead

and Para rubber, retail food prices, prices of textiles, minerals and cereals from 31st July, 1914, to 31st October, 1917, have been deleted, as also the wages of labourers and turners for the same period in four large cities. It was urged that, without any undue straining of analogy, we were in 1918 entitled to deduce from the figures then available of the conditions subsequent to the much smaller war of 1870–71, that there could be no immediate marked fall in either food or material prices. Indeed, as the effects of the war commenced in 1914 were vastly greater, we should certainly have to reckon on a new standard of value for the £ sterling, and also reckon that all conditions of trading would be very difficult during the period subsequent to the war. The assumption in the paper that manufacturing would be controlled in a degree progressively relaxing in its intensity as means of transport and supplies of material permitted greater freedom of trade was ill founded. It was suggested that through wild speculation there might easily be much greater fluctuation in prices of materials in any six months than we had known in any previous six years.]

For years prior to the war we have been accustomed to receive tenders from our leading cable manufacturers based on a sliding scale, say, for paper-insulated lead-sheathed wire-armoured cables, dependent on the market price of lead and copper at the date of acceptance of the contract, the manufacturer gambling on the chance of any loss through increased costs in the other component materials, or increased wages rates, or the increase of his establishment costs by such unpleasant phenomena as a rise in the cost of fuel or in the local rates. On the other hand, there may have been some faint hope that some saving in the cost of manufacture would tend to counterbalance any rise due to other causes.

The author desires to urge the extension of the system of sliding-scale contract prices throughout the engineering industry, and that a tender, say, for an alternating-current generator would state that the tender is based on a price of

l£ per ton for copper
r£ per ton for core plates (unmachined)
s£ per ton for pig iron
t£ per ton for shaft forgings

v shillings per hour for machinists
w shillings per hour for winders
z shillings per hour for unskilled labour

} Rates prevailing in the tenderer's district

and that the tender price will be varied by a defined percentage for each defined rate of fluctuation under each of the above headings as and at the date of the acceptance of the tender.

The instance of the alternating-current generator might be multiplied almost indefinitely. Mutual convenience has established the sliding-scale basis of tendering for cables. Mutual convenience can be secured by the extension of the same principles (allowing also for wages rates) to prime movers of all sorts, to steam boilers, to steel or cast-iron pipes, to transformers, to switchgear, to electric conduits, tramway rails, to motors, or to almost every article that concerns the industry.

The perfecting of the suggested statistical basis must be in the hands of a competent and more or less impartial body One means would be for the Board of Trade or Ministry of Commerce to issue an annual statistical summary with monthly correction sheets. Another means, and one which will probably commend itself most to this Institution, is that the perfecting and application of the sliding-scale basis should rest with a statistical committee appointed by the Council of the Institution. It must be remembered that there are many interests to be served, and that these are perhaps best secured when men with different interests meet round a table. The questions at issue concern manufacturer and purchaser alike, and it is only in this Institution that we meet and can sink our sectional interests, whether as manufacturers or as consultants, in the common weal.

The amount to be allowed for each unit of the defined rate of variation lies with the firm tendering. Their own establishment charges and also estimates of profit are their own concern. Also, too, difference in design

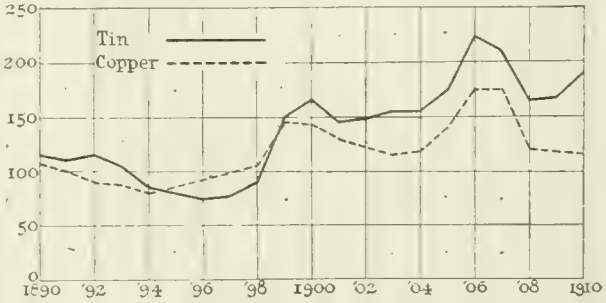

FIG. 6.—Index-numbers for the prices of copper and tin in the United Kingdom, 1890–1910.

may vary the respective quantities, say, of iron and copper for either a motor or transformer of any definite output. The application of the materials is primarily the concern of the manufacturer, and whether he uses x or y lb. of copper in a generator this will, from the point of view of the sliding-scale price, be only represented by $1/m$ or $1/n$ per cent of the tender price for each 1 per cent variation from the standard basis.

The central committee on electrical statistics will be concerned with the base prices for materials and wages, expressed in terms of the agreed index-numbers as and at any convenient period. Two periods suggest themselves—the first is the average price for the eight months ended 31st July, 1914, or alternatively the twelve months ended 31st December, 1917. Or, again, the Committee is not bound to base its index-numbers of prices of component materials on the average price at any period but may select an arbitrary price. The statistical committee having first decided what sums shall be taken as representing 100 in each case, will, at stated frequent intervals, publish its records of prices and wages changes with reference to the index-numbers, circulating these in confidence to manufacturers, purchasers, and consultants. Re-

cipients could fairly be expected to pay the cost of collection and dissemination of these statistics, and also for copies of the model standard clauses defining the application of the sliding scale to all contracts.

Of course the statistical committee is not bound to stop here—it might with advantage summarize the Board of Trade statistics as to food prices, or secure returns as to ocean freight-rates on engineering articles from this, and from competing countries to the chief markets; it might also secure the enumeration of exports and imports of engineering commodities in greater detail through all the several parts of the Empire. Or, again, the statistical committee might also have some direct representatives of the trade unions with which we are in contact. But this is purely speculative, and is perhaps not pertinent to the subject immediately under discussion.

A certain Chancellor of the Exchequer once observed, perhaps in jest, that "we are all Socialists now." Since then we have progressed farther along the lines of State control than any Fabian of that day dare have expected within a century. Whether or not we are to progress farther along the road to the still greater loss of our individualism is uncertain, but it is certain that to a greater or less extent we must all become statisticians—this, even in a branch of the engineering industry which has been more statistically inclined than any other. Units of currency, whether they bear the signature of Sir John Bradbury, or are the now unfamiliar gold piece, are only tokens. They have been made too much a fetish. We have to learn to think of their equivalent purchasing power.

When all is said and done, a very complex civilization depends for its existence upon the barter of manufactured goods or services for food-stuffs. Even under the conditions existing before the war, currency tokens of exchange varied in their real value with variations in rainfall in India and Australia, or the activity of certain insect pests in the Argentine, or other insect pests in the cotton-growing states of the United States, as well as with the progress of human invention and industrial development facilitating bulk production.

It must be remembered that a highly complex civilization which has arisen through systems of intensive development, while in some respects finding its safety in diversity, may yet in other respects be the more liable to accelerated rates of disintegration, dissolution and decay.

Discussion before the North-Western Centre, at Manchester, 9 April, 1918.

Mr. F. Walker: I think all of us will agree that the subject of costs and selling prices and their adjustment in accordance with the fluctuating conditions of the day is of vital importance at the present time. I fear, however, that while the statistics given in the first and second sections of the paper are of undoubted interest, they cannot be of material service in considering the essential parts of the problem. I take the real essence of the paper to be the problem of adjusting costs and selling prices to correspond with changing conditions as to costs of labour and materials, and altered standards of money value, etc. This problem clearly is vital to all, whether in our business capacities as manufacturers of apparatus and suppliers of electrical energy or as purchasers and users thereof, or privately as individuals from the greatly reduced purchasing power of our incomes. I will refer to four phases of the problem, viz. (1) Adjustment of basis selling prices concurrently with changing costs; (2) alterations in cost that occur during execution of contracts; (3) after-the-war completion of contracts now deferred; (4) machinery for regulating contract prices. Dealing with the problem of adjusting selling prices concurrently with alterations in costs, so that discounts may be varied and current prices quoted in tenders without the delay of waiting for actual cost results, it will be found helpful to consider material costs and labour costs separately. No special comments regarding material costs seem to be called for under the present system of Government-controlled and stable prices, but as to labour the position is different. It will be convenient first to consider the influence of labour increases upon a case made up wholly of labour and affected by increases to the full 100 per cent; after which, for cases where the proportion of cost that is affected by labour advances is less than 100 per cent, the required adjustments can be reduced in proportion. As a measure of the cost of labour, and in order to avoid difficulties that arise from different rates paid to different grades of employees on account of different systems of payment, e.g. day-work and piece-work, and from further complications such as overtime and night workers' allowances, it will be found convenient to take as a basis the average earnings of labour per hour obtained by dividing the total earnings of productive labour by the total number of hours worked; then, by multiplying this hourly average by the standard number of hours worked, a fair average weekly wage is obtained, either departmentally, of for the entire works as may be required. Assuming an average wage of 20 shillings, it will be evident that an increase of 1 shilling would mean an additional cost of 5 per cent, and upon weekly earnings of 50 shillings and 100 shillings the increased costs would be 2 per cent and 1 per cent respectively. Supposing only 50 per cent of the total cost to be influenced by labour advances, the additional percentage costs would be half the above amounts, viz. $2\frac{1}{2}$, 1, and $\frac{1}{2}$ per cent respectively. It follows that these percentages can be plotted in curve form, and this has been done in Fig. A, from which the percentage increase in basis cost for each one-shilling advance in the cost of labour can be read directly. In considering the cost of labour it is necessary to take into account not only the actual rate of pay but also the quantity of work produced, as double pay for half output obviously means quadrupled cost, a point of special importance in connection with comparisons of costs incurred during pre-war periods and under present conditions, which in-

volve such a large element of woman and dilutee labour. Having settled the influence of any labour increase on 100 per cent labour, it is necessary to determine for each particular job or class of apparatus the percentage of total price that is affected as labour, and this matter is somewhat complicated. Care must be exercised to include not only productive labour booked to the job, but also labour included in material, in drafting, in erection and in "oncost." Considerable misunderstanding about the "oncost" item appears to exist, so this item may advisedly be gone into a little. It may be pointed out that the "oncost" consists mainly of labour and includes work done by foremen, rate fixers, feed- and speed-men, shop and foundry labourers, shop cleaners, cranemen, power-house and maintenance men, watchmen and shop transport men, cost and estimating clerks, timekeepers, etc., practically all of whose earnings are affected directly by awards. What may be termed "standing charges" properly, such as rent, rates and insurance, constitute actually only a very small proportion of "oncost." In my judgment the general experience throughout the country will be found to be that "oncost" expenses have increased equally with, if not more rapidly than, productive labour so that, for this expenditure to be recovered, the full "oncost" should be included with productive labour in computing the total proportion of cost that is affected by labour advances. It will be convenient next to consider together the second and third points referred to previously, namely, the influence of increases in cost that occur during the execution of contracts, and the position regarding contracts the completion of which is either wholly or partly deferred till after the war, because priority has been given by Government action to other work of greater national importance. In general the great increases that have occurred in costs are well known, but there are one or two points that seem to merit special mention. The following table shows three sets of increases in labour rates due to Government awards:—

	August, 1914	January, 1917	January, 1918	Total Increase divided by 0·9
Skilled day workers	39s.	46s.	66s. 4d.	73s. 6d.
Comparative	100 %	118 %	170 %	189 %
Unskilled day workers	21s.	28s.	46s. 2d.	51s. 2d.
Comparative	100 %	133·3 %	219·5 %	244 %
Women day workers	15s.	19s. 8d.	30s.	33s. 4d.
Comparative	100 %	132 %	200 %	222·2 %

In this table two points should be noted, first that the increase during 1917 is more than double the total increase during the previous period, and second, the corrected figures in the last column showing comparative costs, assuming the output per man-hour reduced to 90 per cent of its pre-war value. In speaking of material costs it must be realized that much of what is termed material by manufacturers consists of wholly or semi-finished parts, which may be bought outside,

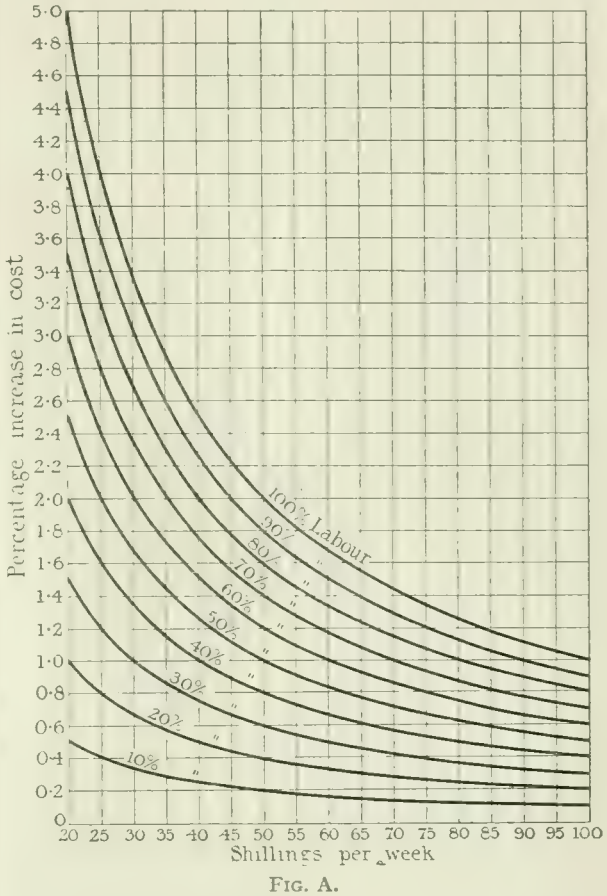

FIG. A.

or even made on "side orders" in the manufacturer's own works, and put into stores to be drawn out as required. The cost of such parts must necessarily reflect increase or decrease in the cost of labour, and, as examples that have been the subject of rapid increase in cost, reference may be made to steel castings and to forgings such as turbine discs and machine shafts. Similar rapid increases have occurred in what from the manufacturer's point of view are raw materials, such

as pig iron, mild steel, iron and steel sections, sheet metals, copper, spelter, lead, etc., though, for some time past, stability in the prices of the metals mentioned has been effected and maintained by Government control. Nevertheless, extra expenditure has frequently been incurred in the purchase of different grades of material in cases where supplies of the regularly used qualities have not been obtainable. From these increases in cost of material and labour, the position has resulted that actual manufacturing costs during the war have greatly exceeded the estimated amount on which the contract prices were based, so that losses have occurred on work already completed or still in progress. Similarly, home and export contracts made before and during the war totalling millions of pounds, on which some work or no work has been done, but which have been suspended either by direct Government order, or indirectly in favour of work of higher priority, or otherwise, can only be completed at costs frequently exceeding the estimated costs by as much as 100 per cent. The question of responsibility for this great excess cost is of great importance. Obviously, to avoid the risk of bankruptcy, the price paid to the manufacturer must be increased by the full value of the increase in cost of labour, material, and overhead charges, with, perhaps, a reasonable profit upon the increases. It may be suggested that the excess should be borne legitimately by the purchaser in all cases where such additional cost can be met by increased charges to the ultimate consumer for whose service the plant or apparatus is intended, e.g. the increased cost of a generating plant could be met by an increased charge for supply of electrical energy. It may be pointed out, in the case of purchasers whose profits are sufficiently large as to come under the scheme of excess profits taxation, that a large proportion of the additional payment (80 per cent on the present basis) would otherwise be paid to the Government. But it is conceivable that cases may arise where such passing on may be impracticable, and where payment of the excess costs would be just as unfair a burden on the purchaser as on the manufacturer, and for relief under such circumstances the Government might be asked not unreasonably to set up a special fund, say, out of the returns from the taxation of excess profits. In this connection special consideration would be necessary as to contracts for export, and perhaps particularly so where purchasers belong to allied or neutral countries. Turning to the question of machinery for regulating contract prices, the author refers to the sliding scale principle which within certain limits has long been in successful use. Examples that may be cited are the purchase of coal according to its calorific value, the variation of charges for electrical energy according to the price paid for coal, and the sale of large electrical machines and surface condensers subject to variations in the current prices of copper and of condenser tubes and plates. The extended application of this principle should be quite practicable in cases where the quantity of any one material included in the product is sufficient to warrant its use, but this condition, speaking generally of electrical and allied apparatus, would appear to be rather the exception than the rule. During the last few months a method of price adjustment for labour awards that has been generally adopted in contracts is what is known as the Variable Price Clause, the essence of which is that " For each one shilling per week by which the rate of labour is increased by authorization of the Government the contract price shall be increased by an amount corresponding to $1\frac{1}{2}$ per cent of the contract value, or pro rata. Such increase in the contract price is to be in the same proportion as the unexpired period of the contract is to the total contract period." It is desirable to point out that, while an increase in price of $1\frac{1}{2}$ per cent for each shilling will be found very nearly correct on the basis of present-day labour costs, a considerably greater percentage would be necessary for use in connection with pre-war costs. In working out the percentage per shilling for use with any basis wage to return excess costs for labour occurring during the execution of contracts, it is necessary to realize that after acceptance of an order and before commencing productive manufacture a certain period is necessarily occupied in setting up and working out details, preparing drawings, extracting quantities, ordering up and waiting for delivery of materials, etc., and in making any patterns, jigs, templates, tools and discs, etc., that may be necessary. This means that the labour costs in manufacturing are incurred mainly during the latter part of the contract period, and allowance for this is necessary in setting up the percentage per shilling, e.g. for a time-lag of 25 per cent of the contract period the correction would be to multiply the apparent percentage by $\frac{4}{3}$.

Mr. A. J. Stubbs: In regard to the terms under which tender prices may be adjusted it is important that provision be made for adjustment as from the date of the tender, and not from the date of the contract. In some Government work the date of the contract may necessarily be long after the date of the tender (it may be a month or two months or even more), and as it might be necessary to insist upon strict interpretation of the term used; variations which occurred between the dates of the tendering for and of the placing of the contract would in such case be precluded from allowance.

Mr. S. L. Pearce: I think we can agree, whether we are buyers or sellers, that an extension of the sliding scale would have its advantages, bearing in mind, of course, that a sliding scale might be up or down. I rather share Mr. Walker's view that an extension of the sliding scale would have its limitations. There are certain obvious raw materials which could be subjected to a sliding scale, but one cannot push the idea to extremes. It might be applied to standard articles, but there must be quite a number of other cases where it would be difficult to base a contract upon a sliding scale for materials. If contracts were formulated on that basis there could not be any very great divergence in the prices that would be submitted by different firms. That is alluded to by the author on page 875 where he instances that firms would be entitled to get credit for a difference in design, but when all is said and done prices would approximate very closely one to another. It therefore seems to me the tendency will be practically to drive all manufacturers of a certain class of electrical goods into an association such as exists to-day in connection with certain manufactures. It seems to me that would be an inevitable tendency for the time, if

a sliding scale were adopted, until we can return to what the author terms the regime of an "unfettered individualism." I agree with what was said by a previous speaker, that a system of contracts on a sliding scale would have to be made compulsory. It would have to apply to all or else the aim of the author would not be secured.

Alderman W. Walker: Mr. Stubbs raised the question of the time-lag between the receipt and the acceptance of a tender and the effect of an increase in prices in the intervening period. I have noticed that many tenders, during the last 12 months at any rate, contain a clause giving a very short period for acceptance. By this means the manufacturer can compel the purchaser to decide within a reasonable period instead of running into months as Mr. Stubbs suggests has been done. Another point raised was as to the purchaser preferring a firm price to an indefinite sliding scale. That would entirely depend upon whether all the components affecting the price were brought into the scale; if so there would not be room for excessive variations, but otherwise the purchaser would fear that the ultimate cost would be very much in excess of the basic price of the tender. On page 875 the author says, "Rates prevailing in the tenderer's district." That, it seems to me, would penalize certain districts. Take the areas round the city of Manchester—manufacturing areas. Wages are always high in those districts, much higher than in some other districts where similar plant is being produced, and therefore the factors which counterbalance the foregoing advantages would have to be brought into the scale to maintain equality of conditions. Mr. Walker raised the question of overhead charges. My own experience is that the non-productive labour ought to be made a percentage charge on the total output. I do not know whether Mr. Walker has found that inapplicable to the particular type of contract he had in mind, but it has met most of the cases I have had to do with in various business experiences. I agree there is a tendency sometimes to overlook them, and yet they have a very relative importance to the actual cost of production. I think with Mr. Pearce that the inevitable result of the adoption of the sliding scale system will be to bring together the manufacturers. In some branches that is already being done, for the purpose of arranging terms and conditions. I do not think it is a bad plan. The purchaser, after all, can prevent it being carried to an extreme and I do not consider that the combination of the manufacturers, so far as it has gone, has been bad for the industries concerned. It is not really beneficial to have manufacturers competing to the extent they did at one time, and offering plant at prices that could not possibly pay them. From a national point of view it is a bad policy. There is one other question I should like to ask the author. Supposing a firm has purchased sufficient raw material to cover all its manufacturing requirements for a considerable period ahead, and that in the meantime and when the quotations are being made, the price has gone up. Is that firm not to take advantage of having purchased at an extremely low rate one of the principal components, say copper, entering into the contract, or are all the tenderers to be put on the same mark, viz. the price of copper at the date of the tender? If so, then the advantage of the knowledge that some firms have of the right time to purchase will be nullified.

Mr. L. B. Atkinson (*communicated*): The question of index-numbers based upon an assumed gold currency requires to be fully discussed. It is perfectly true that prices rise or fall in relation to large and small quantities of currency, and it is generally assumed that the price and quantity of currency are related as effect and cause. I think that this is not entirely true. When there is a large demand, and that demand is being satisfied, it is true, as a rule, that prices will be high. It is also true that a large amount of currency is in circulation. But I think the prices are high because the demand is large, and not because there is a large amount of currency in circulation. The currency is in circulation because the demand is large and is being supplied.

Mr. W. M. Furniss (*communicated*): I quite agree that any honest trading firm must welcome a sliding scale scheme for prices of electrical machinery, and I see really no other way than the percentage scheme which the author puts forward. I realize, however, that it is comparatively easy on standard plant, but will mean very considerable work on all special quotations.

Mr. J. H. St. H. Mawdsley (*communicated*): The author's suggested application of sliding scale contract prices to the engineering industry would be very welcome. Such a scheme would relieve the manufacturer of a good deal of risk which he has been obliged to take in the past, and with the element of risk obviated closer prices could no doubt be quoted, but unless the adoption of a sliding scale system is made obligatory I am afraid it would not work for any length of time, for the purchaser also will not wish to take risks, and if one manufacturer quoted a firm price and another manufacturer a price subject to a number of indefinite factors, it is nearly certain that the firm price would secure the order and the sliding scale system would soon go by the board. Further, we cannot treat this question in an insular fashion. Other nations have also largely increased their manufacturing facilities and will want business after the war, and even if they adopted a similar system of sliding scales they would not be likely to stipulate for the same percentages. The problem of the future will therefore be to a greater extent than ever the reduction of costs, taking into account the practical certainty of a continuing high level of wages. High wages to be permanent and economically sound must be associated with high production, and, if we are to judge by pre-war history, a campaign to bring home to Labour the fact that high wages and high production are one and not to be permanently divorced either by masters or trade unions would seem to be very necessary. We are apt to forget that what is obvious to us may not be equally obvious to others, and the effect of increased production and consequent lower percentage establishment charges in reducing the cost of an article is apparently not understood by many people, who appear to think that the cost of an article is simply dependent on the cost of labour and material.

Captain W. P. Digby (*in reply*): I must explain

to Mr. Walker that in citing the figures throwing light on the economic situation after the Franco-Prussian War I was well aware of their limitations. Mr. Walker's exposition of the existing Variable Price Clause is lucid. Yet while the clause as explained by him is possibly equitable in its results, I regard its wording as lacking in clarity of definition, and feel that its application may be fallacious. According to my understanding of Mr. Walker's exposition the key upon which increases hinge (there is no provision for any decrease) is the weekly wages rate paid to all productive labour. Now the relative proportions of skilled artisans, unskilled labour and female labour are to-day in a continual state of flux in any large firm. Comparing the different firms making the same class of goods, Mr. Walker will find yet other ratios of these three classes. Advances for the three classes are not synchronous, and a firm employing more of one class than its rivals may be prejudiced by the present phrasing of the clause. Even in the same works, one class of product may be made wholly by the skilled artisan. I agree that the present Variable Price Clause might be further modified to allow for the time-lag between placing the order and the actual starting of work in the shops. Mr. Walker does not approve of my reference to a future saner unfettered individualism; I had thought that this aspiration was almost universal, and had never anticipated its being regarded as heterodox in such a haven of individualism as Manchester. Yet while the phrase is criticized I am not at all sure that a saner unfettered individualism is in any way incompatible with the spirit of mutual help and the principle of a square deal for all parties concerned.

In reply to Mr. Pearce, I am not quite sure whether the introduction of a sliding scale system of tendering will really tend to strengthen what I may term the "ring" system of tendering. I sometimes think that a sliding scale system of tendering might even weaken some phases of the ring system. To apply the principle of the sliding scale to such things as condensers, water-tube boilers, turbo-alternators, or big power-house transformers is easy, but if we are to apply it to such things as switchboard instruments and so forth, where material is negligible and labour is the main cost, the operation of the sliding scale would be governed more by the cost of labour than by the cost of materials. I am not at all certain that the sliding scale system would have to be compulsory. A purchaser might ask for tenders on a sliding scale basis and a firm might prefer to gamble in regard to price. Speaking for myself, I should certainly prefer to advise purchasers to buy on the sliding scale which should, in my opinion, give a closer price than on the other system.

Alderman Walker referred to the question of rates prevailing in the manufacturer's district. I am afraid one cannot get away from that expression. He also raised the question of firms with big stocks. If a firm has a big stock purchased judiciously, I can see no reason whatever why they should not make a profit from it.

I am glad to have the support of manufacturers like Mr. Furniss and Mr. Mawdsley of a sliding scale proposal. But I do not share Mr. Mawdsley's view that a universal adoption of the sliding scale is necessary; I feel that closer equitable prices can be obtained, and I do not think the buyer will be prejudiced. As regards any increase in wages after expiration of the contract period, any benefit ascribing to the manufacturer should be counterbalanced by a penalty for late delivery.

DISCUSSION ON "LARGE POWER TRANSFORMERS."*

North Midland Centre, at Leeds, 13 January, 1920.

Mr. C. J. Stacey: I consider that the springs used for automatic adjustment to compensate for shrinkage on core-type windings are not so advantageous as some firms would try to make us believe. The idea is very effective, but if the spring has expanded to take up the necessary shrinkage, the pressure of the spring will be reduced. If, under these conditions, the transformer is required to withstand a heavy rush of current, the windings will be forced against the pressure of the springs and will press the springs back to their original positions, thus allowing the windings to have considerable axial movement, which is very undesirable. I am strongly in favour of frequent inspection and tightening of the adjustable bolts (with springs), and under these conditions the windings are held secure between solid supports. I should also like to point out that very little attention is paid to the use of simple guides inside the transformer tanks to keep the core steady during the operation of taking it out or replacing it in its correct position, and I have seen windings damaged, both in the maker's works and also on site, owing to it being impossible to steady the core when suspended inside the tank during raising or lowering operations. There is a point in favour of strong, flat, solid bases for transformer tanks, as it is much more convenient to transport transformers across soft ground on loose rollers or tubes, than to use the type of wheels which are usually fitted to transformer tanks. Also, a very simple removable transport fender can be fitted, which will protect the tank from damage when being transported through narrow openings such as substation doorways or openings to the transformer chamber. Suppose that during slinging or rolling operations the tank fitted with fenders came forcibly against any structures; the protection fender would receive the force of the collision and thus protect the tubes of the tank, as the fender projects just beyond the tubes. Two different types of skids and fenders are shown in Figs. A and B herewith. Fig. A illustrates skids made up of channel irons, or of two pieces of angle irons riveted together to form a Z-shaped iron. The fenders can be easily taken off when more room is required, by unfastening the bolts shown in the plan and the bolts which fasten the fender to the skids under the tank. Fig. B shows another arrangement of skids, and in this case H-iron with a tie-bolt across the centre is used instead of channel iron. In both cases the fenders are very useful for levering purposes. I do not altogether agree with the authors' view regarding the British Standard Rating. It is rather a difficult proposition for a supply company which has several hundreds of transformers in service to change from the old method of ordering transformers to the British Standard Rating. These transformers were designed to give 20 per cent overload continuously, and if the British Standard Ratings were now adopted, all the present transformer records would need to be altered correspondingly. I have recently received a quotation from a British maker for a number of transformers of various sizes, both for units capable of supplying 20 per cent overload continuously and also for units to the British Standard Rating, and I find the British Standard Rating to be in all cases the most expensive per kilovolt-ampere of maximum output. I regret that the authors have not dealt at length with the question of voltage

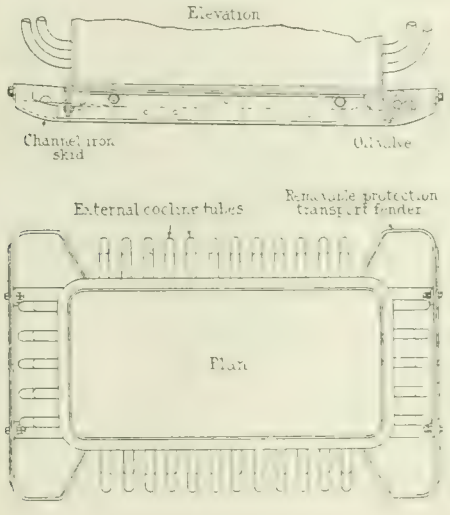

Fig. A.

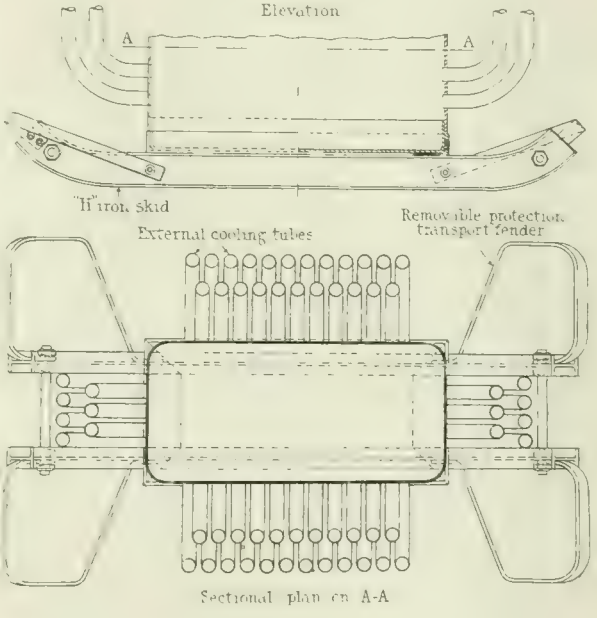

Fig. B.

* Paper by Messrs. A. G. Ellis and J. L. Thompson (see vol. 57, p. 547)

regulation of interlinking transformers. My experience leads me to believe that the transformer makers of this country will need to develop the switchgear or controlling gear for the regulation of voltage, as these units must be supplied complete; the present gear for large units does not give very satisfactory results, and some makers will not undertake to manufacture or supply gear for regulating large units.

Mr. W. E. Burnand: I notice that the authors strongly advise despatching the transformers complete with oil wherever possible. I am in favour of this method, but sometimes the railway companies object. They point out that if they lay a transformer on its side some of the oil escapes, but they do not explain why they put it on its side, when it is easier to handle it right side up. On the matter of substations, I think the authors do right to insist that there should be plenty of fresh air. If we get a temperature of 100° F. in the substation we must expect the transformer to run hot. In that connection, chimneys are of very little use. I have seen chimneys fitted in substations 6 ft. high, and the air comes down as often as it goes up. What we want is plenty of area in the opening of the substation to let the natural movement of the air determine the volume of the air passed through the substation, or to help it through with a fan. The chimneys are of very little use. Regarding internal versus external reactance, I favour external. If it is internal it increases the stresses and introduces additional risks. We cannot insert these iron shunts, or even regroup the coils, without a certain amount of complication and loss in efficiency, whereas with external reactance we get transformers of the highest efficiency and are able to alter the reactance without disturbing the transformer. It also takes to a great extent the shocks, due to surges of steep wave-front, from the end turns of the transformers. The insulation and mechanical staying of the external reactance is a much simpler matter than with internal reactance. The authors point out the great stresses that occur on large transformers on the big power systems, and they also mention that during the last decade the size of plant in all power stations has increased practically tenfold. If it is going to increase tenfold in the next decade—and I do not think there is much reason to doubt it—the ordinary form of transformer will not stand the increased stresses. If we are going to get 2,000 tons stress, and 70 tons per square inch on the outside coil, it is obvious we shall have to develop some other construction or prevent the current from attaining anything like its full value. In that connection I should like to mention one or two types of transformers not referred to in the paper. There is one, for which I am responsible, with a square core and the coils distributed on each leg of the core. Inside the square it is held up as in the shell transformer; whilst outside, the coil splits up into four and the coils are triangular in cross-section. In that way, only a quarter of the coils are in a section outside the core and, in addition, the coils as they get further from the support of the core become smaller in width with fewer turns. Thus, for a given rating of transformer, quite a light bracing is sufficient to withstand the ordinary stresses. This is useful, but would not get over the stress difficulty indefinitely; for instance, for sizes 10 times the largest now contemplated. There is another type I saw at the old Paris Exhibition. The Ganz firm had some transformers like a Gramme ring, and of about 5 kw. I do not think one could say anything good about them in that small size; they were inefficient, expensive, and not very reliable. It seems possible in these extra large sizes that the design might be considered and developed. If we adopt this type, distribute the windings evenly round it, and bow out the windings so that the final shape of the transformer is something like an orange, the stresses are balanced among themselves. Whatever stress is on any turn is balanced by an equal stress in the opposite direction, except radially in the outer layer. Thus there is no tendency to deform the windings. I have no personal experience of the design, but it looks feasible now that bracing, though quite unimportant a few years ago, seems likely to become a determining feature. Going beyond that, I will draw a more or less fancy picture. The point is: Is it not possible to get a radically different design? The first thing that occurs to me is whether we can omit the iron from the transformer. If we get a 200-kw. transformer we might have 1 per cent magnetizing current with the iron working at a permeability of 2,000. If we omit the iron we get 20 times full-load current through the transformer on no load. That is evidently unpractical. As the size increases, say with the same magnetic and electric densities, the magnetizing current decreases slowly. Consider a large size, say 250,000 kw. We shall get approximately one-sixth of that percentage magnetizing current. That still amounts at no load to $3\frac{1}{3}$ times full-load current. If we make a transformer without iron we should naturally modify the shape and perhaps put more turns in the windings. By that means we might bring the magnetizing current down to, say, one-tenth its former value, but, as it still leaves 33 per cent of full-load current for magnetizing, apparently we cannot do without iron. Here another factor might be considered. It has been shown that a few degrees above absolute zero temperature certain metals, or possibly all pure metals, have practically zero resistance. That means we can use a very small cross-section and increase the number of turns. We might increase them 10 times, for instance. This would reduce the voltage between adjacent turns, and the metal would cost practically nothing owing to the small area, the magnetizing current decreasing as the square of the number of turns. Thus, on the large size of 250,000 kw., one-third of 1 per cent would be required for magnetizing current without using iron. Even for 25,000 kw. we could still have under 1 per cent of magnetizing current. At such a temperature we should obviously embed the attenuated coil in a block of ice—not necessarily frozen water but perhaps solidified air. Imagine we have this simple coil embedded in a solid block of ice at approximately absolute zero temperature. There would be no iron losses and no resistance losses, and instead of the problem being to get heat out of the transformer it would be to prevent heat getting in, and the solid block of ice of the highest insulating qualities (even clear frozen water is a good insulator, but no doubt there are many better and stronger)

would prevent displacement or vibration of the windings. There is room for plenty of research in that direction.

Mr. F. S. G. Hinings: In the paper the authors have given their experience and opinions of various types of transformers, and these are more or less in harmony with my own. Analysing the advantages and disadvantages put forward by them of the core and shell types, they have made out a case in favour of the latter. There are, however, a few points in favour of the core type, so I feel sure that we are all picturing in our minds what the ideal transformer must be like in order to combine all the good features of both types. One of the merits of the core type, the authors tell us, is that the windings are circular, which simplifies the insulation problem. Now, if it is advantageous to have circular coils in the core type it must also be so with the shell type, which of course it is. In accordance therefore with the authors' remarks the "ideal transformer" must be a circular shell type. The one illustrated in Fig. 12 (vol. 57, p. 559) has rectangular coils and hardly meets the ideal. The authors further state that the windings of a core-type transformer are more liable to shrink on account of the weight of the copper in the windings. The obvious way to counteract such a defect is to use a more mechanical insulation which does not shrink, no matter what the pressure. Insulation of this kind has been used for many years. As regards shrinkage of windings, I can say that experiments and inspections have shown, as claimed by the authors for the shell type, that shrinkage is negligible, so that automatic or any adjusting clamps for the coils are really unnecessary except in very large sizes. The use of automatic spring adjustments necessitates a construction which is not so rigid as would be obtained if such apparatus were omitted, since obviously, unless the coils do move and can move, the spring adjustments would be valueless and the restrictions must be such that the springs can overcome them. Such construction implies less rigidity, with a further disadvantage that it is possible under certain conditions for the reactance to be affected, with serious results as regards parallel operation. There is no doubt that springs or any other automatic adjustments of coils introduce complications which should be avoided, and it is possible to avoid the use of such devices if the transformer itself is built rigid enough to withstand the severe conditions of service without movement of its coils. I was rather interested in reading an advertisement in the electrical Press the other day by one of the manufacturers mentioned in this paper who makes core-type transformers. They stated that the chief feature of their transformer is that it has no gadgets—no spring devices which cause more trouble than they cure. Table 6 gives the voltage per turn for the core and shell types, and it will be seen that in the core type the voltage per turn is much less than in the shell type, and the authors tell us that the insulation between the turns must be heavier for the shell type on that account. If, however, we turn to Table 7 (vol. 57, p. 566) we note that the breakdown voltage between turns of either type is several thousand volts, and the average safe voltage in practice is from 166 to 900 volts. The minimum practicable thickness of insulation between turns is fixed chiefly by mechanical considerations and not by electrical.

Mr. F. A. Lauper: Can the authors tell us how the extra losses increase with the use of magnetic shunts? It is well known that in designing transformers with high internal reactance the additional losses in copper and iron increase proportionately, and consequently also the heating. Very often the trouble with magnetic shunts in the past was excessive local heating, but I suppose that with present designs it has been largely overcome by using laminated and insulated constructions. How do these extra losses in transformers with magnetic shunts compare with those where internal reactance is used? I should also like to know how the authors propose to fix the coils on big transformers for electric furnace work, where the currents attain very high values and the whole service is usually much more severe than for either lighting or power purposes. The big copper sections required are not easily made mechanically rigid. Due to the working of the furnace, we have very frequent short-circuit conditions, where the stresses in the windings can attain excessively high values. How do the authors propose to face these difficulties?

Mr. S. E. Fedden: I disagree with the use of such devices as spring adjusters, and I also do not approve of having continually to adjust one's transformers by screwing down the nuts to hold the cores tight. One installs a transformer and wants to use it continuously, and it seems to me a weak point in construction if we have to put the transformer out of commission for adjustments. I am a user of both core and shell type transformers, and of course there are failures with both types, but nothing like as many as there used to be years ago. I went in for manufacturing transformers twenty years ago, because I had such a bad time with breakdowns. The transformers were made under Mr. Burnand's patents, and many thousand kilowatts of them were produced in the Corporation factory at Sheffield, and I can say that many of them, designed for a short-period lighting load, are running to-day after 16 years on a long-period power load. I have water-cooled oil transformers in use and have never had any trouble with them. Coils of lead pipes through which the cooling water circulates are immersed in the oil at the top of the tank. In my new power station I am installing transformers which will have oil circulation, water-cooled, and the oil will be kept at a higher pressure than the water, which will ensure that no water gets into the oil. I am trying a new idea in these transformers. The main 6,600/11,400-volt transformers will be tied to the alternator, and another coil to supply 440 volts is to be provided for the station auxiliary plant, so that the main plant will run its own auxiliaries. I do not know if I shall have any trouble, but perhaps the authors will tell me if I am taking any great risk. Up to now I have always advocated three single-phase transformers in preference to a three-phase transformer, on account of less expense in spares. If we have a substation with a lot of three-phase transformers, it may be more economical to put in three-phase sets and keep three-phase spares. I agree with the authors when they say we may have too high an efficiency with a loss in durability, and I think we can strive for high efficiency

and get lots of breakdowns. There is one question which I should like to ask in connection with the installation of large three-phase units in preference to single-phase units. On a job where there are large fluctuations on any phase I am of opinion that the large three-phase transformers would not be satisfactory owing to the long yoke. It is necessary to have a very long yoke because the three coils are in line. If we get a big out-of-balance load it seems to me there would be a great tendency to displace the yoke and cause more adjustments than ever to be made. Perhaps the authors have had some experience with regard to large three-phase units on heavy duty with out-of-balance load.

Messrs. A. G. Ellis and **J. L. Thompson** *(in reply, communicated)*: Referring to Mr. Stacey's remarks on the use of springs for automatic compensation for shrinkage of the windings, the disabilities of springs which he mentioned were pointed out in the paper, and these disabilities are overcome by the use of the oil dash-pot, which prevents the sudden movement that would take place if the springs were free to compress. Regarding the question of the B.E.S.A. Rating, if everyone took Mr. Stacey's standpoint as regards alteration of records, no progress would ever be made in such important matters as standardization of rating. It is a relatively simple matter to determine the B.E.S.A. Rating for any existing transformers, and to have this stamped on the rating plate in addition to the existing rating and temperature rise. The fact that a large number of supply systems in this country have already adopted the B.E.S.A. Rating shows that there are no serious disabilities to this step; and the advantages of a common basis of rating, to both users and manufacturers, are quite apparent. The reason why the B.E.S.A. rated transformer of a certain output is, in the case cited by Mr. Stacey, more expensive than a transformer for the same output considered as a 20 per cent continuous overload, is probably that the temperature rise allowed on the continuous overload is 60 degrees C., whereas the B.E.S.A. Rating is 50 degrees C.

Regarding voltage regulation of interlinking transformers, the induction regulator is available in this country, and certain contact regulators can also be obtained. With regard to Mr. Burnand's remarks, it is true that the external protective reactance has the advantages mentioned, but, in stating that a transformer with protective reactance external instead of internal has a higher efficiency, Mr. Burnand has overlooked the fact that there are considerable losses in the external reactance which must be taken into account.

Mr. Hinings refers to the circular-coil shell-type transformer which is virtually the underlying principle of the Berry design. The reason why the circular coils are not generally used for ordinary shell-type transformers, is that the construction would be considerably more complicated, especially from the manufacturing point of view, and would be more costly. The rectangular-coil shell-type transformer has been built in this country and in America and Europe for a total of many millions of kilovolt-amperes, and has proved itself a thoroughly sound design. This is a case where the "ideal" is not always the practical solution. Mr. Hinings states that the use of automatic shrinkage devices introduces complications, and he refers to an advertisement stating that such devices cause more trouble than they cure. If he were to investigate this matter he might find that the party responsible for this advertisement had not used such devices and cannot therefore speak from experience. The authors have had a large number of transformers built fitted with the spring dash-pot coil support, with very satisfactory results.

In reply to Mr. Lauper's remarks, the use of magnetic shunts for high-reactance transformers, designed to the authors' patent No. 110,070 of 1917, effects a large reduction in the eddy-current losses, and has, in fact, improved the efficiency of such transformers by about 0·2 per cent.

Referring to electric furnace transformers, the low-tension coils are usually made of copper strip wound on edge, which gives a very rigid winding. Electric furnace transformers are dealt with more fully in Mr. Thompson's paper * on that subject.

In reply to Mr. Fedden, the tightening of the adjusting screws on the spring dash-pot coil supports is only necessary occasionally, since the springs automatically take up the shrinkage, which would otherwise leave the coils free to move. With the large sizes of transformers at present required, periodic inspection is far from undesirable, and on such occasions the tightening up of the coil bracing screws is a very simple matter. Regarding the auxiliary winding for 440 volts on Mr. Fedden's main 6,600/11,400-volt transformers, this has already been done on very large generating station transformers, and, provided the winding is properly supported and insulated, it should cause no trouble. The authors have not experienced displacements of the yoke in three-phase transformers, and this seems to them impossible if the transformer is properly designed and constructed.

* *Journal I.E.E.* 1920, vol. 58, p. 201.

Western Centre, at Cardiff, 3 February, 1920.

Mr. Arthur Ellis: The authors have referred to lack of opportunities for building large transformers in this country. If this is so, I am of opinion that such opportunities will be amply afforded in future years under the new schemes which will be evolved as a result of the Electricity Supply Act for the production and distribution of electricity generally. Manufacturers will no doubt lay themselves out to produce transformers of large power, such as are referred to in the paper, and as are used in the United States and on the Continent, in view of the larger units which are going to be utilized for public supplies. After all, I think it will be agreed that, if and so long as transformers are properly designed, there is no reason why supply engineers should not rely upon transformer manufacturers, as they do upon manufacturers of other plant, for reliability, efficiency,

etc. In regard to the sizes of transformers, it is suggested in the paper that to some extent they are controlled by crane capacities. When one bears in mind the sizes of units and the weights to be lifted, and the cost of such units, even though it may entail the additional expenditure of a few hundred pounds, that money—representing only a small proportion of the total expenditure—would surely be well spent in providing cranes of ample capacity for dealing with the installation of large transformers. In regard to transport difficulties, as suggested in Figs. 1 (*a*) and 1 (*b*) of the paper, it is possible that the Ministry of Transport will have the matter before them and provide such arrangements as will remove the present difficulties. In regard to cooling, I do not think it needs much understanding of transformer problems to appreciate that transformers, over and above 5,000 k.v.a. capacity, should be forced cooled. Some of us have held this view, even in regard to transformers having smaller capacity than this. In regard to the question of single-phase versus three-phase units, the authors' remarks are very interesting, particularly in regard to the difference in weights and costs as between 25 periods and 50 periods respectively. This is a matter upon which no doubt Mr. Chamen, of the South Wales Power Company, whose system is operating with a periodicity of 25, will be able to express his views, whilst those of us connected with 50-period undertakings may presumably congratulate ourselves that our transformers do not cost as much as they otherwise would do. No doubt there are advantages both ways. The authors have tabulated the respective costs of three-phase and single-phase units, and reference is made to the percentage of spares to be carried, but I suggest that to carry one spare for every six transformers where, say, 10 groups are installed, is somewhat on the high side, but even when laying out a power station of 250,000 k.v.a. capacity, it is not desirable to have so much money lying idle, which may be £32,500 in one case and £37,000 in the other. In regard to types of transformers, the authors have clearly illustrated the core and shell types. Personally I think the former type has many advantages over the latter. The authors have shown us what it means when one leg of a transformer breaks down and one has to dismantle the whole structure to effect a repair. With the core type, however, one need not keep a spare transformer in stock, but merely spare coils, which can be more readily fitted, thus effecting a saving of time. I certainly agree with the authors that the British Engineering Standard Ratings ought to be adhered to. Some of us have, not only in regard to transformers, but for electrical machinery in general, stipulated that certain overloads must be carried for certain periods of time. I certainly think it would be better if we could take into account immediately the possible overloads to be carried and the length of time over which they would extend, and then put it up to the manufacturers to provide a transformer that would be capable of meeting such requirements. I should hesitate to act upon the authors' advice where it is stated that the correct way of switching in is to close the switch slowly, during which interval the distance between the contacts becomes smaller, until the voltage causes the current to jump across the gaps. This is a practice which I have never followed. On the contrary, I should do quite the reverse. No doubt the authors have satisfied themselves that no injurious effect takes place at the terminals or contacts. There is, in my opinion, no reason why designers of transformers should not produce something which will be entirely reliable in the same sense as are the prime movers. What has occurred to me is this: There are various manufacturers who have different designs, and all of them try to persuade the engineer that their particular design is best. I think it would be desirable for designers of transformers to cut out any idea of competitive designs and to combine the best points in each, in order to produce that which will give ideal results. I see no difficulty in this being done. Supply engineers would then be relieved of many anxieties and cares in endeavouring to maintain public supplies, and, even if a transformer breaks down, we shall have the satisfaction of knowing that it was through some exceptional cause, and not as a result of the purchase of an inferior article for the benefit of the lower price.

Mr. W. A. Chamen: For some reason I do not quite understand, I seem to be always expected to say that a periodicity of 25 is better than any other. The point really is that in this district there is a very large amount of 25-period plant at work, and I do not see how it is going to be got rid of. 25 periods is better for some purposes, while 50 periods may be better for others. The fact that 25-period transformers weigh and cost much more than 50-period ones may not really have a serious effect upon the question, because the transformer is not the controlling factor. If it were, why not increase the periodicity to 100 and so presumably reduce the weight and cost still more? Those who originally decided upon 25 periods for the South Wales Electrical Power Distribution Company's system did, I believe, seriously consider adopting 15 periods, but in the end 25 periods was decided upon as probably being sufficiently low to secure to a very considerable extent the advantages of low periodicity, without seriously accentuating the disadvantages. The problem we have to face is that of working the two periodicities together, or, if one ought really ultimately to prevail, to find out how, gradually, to make the change (it cannot be done suddenly) from the one periodicity to the other. Bearing in mind all the brain work and ingenuity that have been expended on transformer problems, why cannot someone devise a static frequency changer? A system of transmission and main distribution at 25 periods, with the possibility of transforming to higher periodicities where desired, while leaving 25 periods available for large motors, rotary converters, etc., would seem to be an excellent solution if it could be arrived at. I am glad to hear what the authors say with reference to the use of auto-transformers for stepping-up and down, to and from very high pressures. I had arrived at the same conclusions myself when considering this question some years back, although the plant then in contemplation was not installed. The trouble caused by the shrinkage of

insulation material is one upon which we have had considerable experience. I should like to know whether the automatic device for following up shrinkage with springs combined with dash-pots has been put to the test and found to perform the duty for which it is designed.

Mr. A. J. Newman : Although the paper was written something like a year ago, progress, I take it, has not been so rapid as to cause the data given to be in any way out-of-date. My remarks would not be in the nature of criticism, but would take the form of seeking information. I personally should like to know how much, in the authors' opinion, the costs per kilovolt-ampere have been increased since the figures were compiled. I notice that the authors do not apparently attach much importance to road transport, though I should have thought this method of conveyance should have received some little consideration. I quite agree with the authors that wherever possible transformers should be delivered in their tanks covered with oil. It has, however, been my experience that, even when transformers have been so delivered, drying has had to be resorted to, owing to water finding its way into the tanks on account of exposure and delay in transit. The authors give us no particulars of weather-proof transformers suitable for use in the open. I understand it is common practice in Canada to install both transformers and switchgear without any protection whatever from the weather. No mention appears to be made of utilizing the latent heat of vaporization of water in dissipating the heat due to losses in transformers. I take it this method has been employed, but presumably the success attained did not warrant the giving of details in the paper. Personally I have never favoured three-phase transformers, owing to the difficulty in handling, loss in efficiency, and greater cost when spares are taken into account. There is certainly a great saving in floor space, and one must not lose sight of the fact that the external connections in the case of single-phase transformers are not easy to deal with, and are indeed a costly item. Is it not true that there is a greater difference in the case of a three-phase transformer between the hottest point and the average temperature of the oil ? On page 556 (vol. 57) I notice the authors make no differentiation between the annual charges in respect to iron and those pertaining to copper losses. An old-time figure I remember using was one shilling per watt for iron losses, but this was based on considerably under $\frac{1}{4}$d. per unit for 100 per cent load factor units. If we take the authors' figure of $\frac{3}{8}$d., and the present-day value of money, the 1s. referred to becomes something like 2s. 8d. per watt. Now, if we compare the single-phase and three-phase propositions in Table 4, we have 5 kw. iron loss in favour of the single-phase. This at 2s. 8d. per watt is equal to £666, a fairly substantial item, amounting as it does to about $12\frac{1}{2}$ per cent of the cost of the three-phase transformers and being more than adequate to provide the extra expense of external connections. The enormous shrinkage in insulation is extremely interesting. Although I quite appreciate a certain amount of shrinkage would naturally take place, I had no idea it was of such a large order. I should like to know if the factors of safety are very much lessened as a result of this.

Major E. I. David : In connection with the curves on page 550 (vol. 57), I observe that the curves for costs of self-cooled transformers assume a very flat state at about 5,000 k.v.a., which is an important point in considering larger units. The weights per kilowatt also increase for machines over 3,000 k.v.a. No one is going to install larger units if they do not cost less per kilowatt than smaller ones. The water-cooled and forced-cooled curves do not flatten out until well over 20,000 k.v.a. I do not think we shall arrive at that flat point in this district for some time. Reference has been made to the Manchester-Salford link as having the highest voltage in this country. In this district we have a 38,000-volt system (at present working at 22,000 volts) connecting two large power schemes at a distance of 10 miles, namely, the line between Bargoed and Aberaman. The total kilowatt capacity at one end is 16,000, and at the other end 12,500. This system of mains is being extended at the present time, and when complete will form a triangular system consisting of three legs, each approximately 10 to 11 miles, with feeding-in and feeding-out stations at three or four points. The existing line has induction regulators, but the line can be run without them, as it is possible to transmit power when the voltage of the transmitting station is less than that of the receiving station. The regulators are not necessary except to maintain the power factor, and as the receiving station has synchronous power-factor-improving apparatus and also a large phase advancer, they could be dispensed with in this case. In connection with this particular system, we have installed two 3,300-k.v.a. three-phase transformers at each end. These are of the forced-cooled type. There is one point which apparently has not occurred to some of the previous speakers in connection with forced cooling, namely, the enormous losses of oil to which this type of transformer is subject. Our make-up oil in one 3,300-k.v.a. transformer was 160 gallons for three months, and this was simply leakage of glands and pumps in the pipe range. All the joints in the pipe range are welded, but the greatest leakage, so far as we can trace, is in the coolers. It is necessary to have the pressure of oil greater than the pressure of water, otherwise there is leakage of water into the oil. The particular cooler we use is supposed to be absolutely immune from leakage. The tube plates are made of thick metal with soldered ends to ensure a tight job. The only thing we can assume is, that there are either minute pinholes in the tubes or cracks in the tube plates or in the joints. If the make-up oil is going to be 160 gallons in three months, that represents something like £160 worth of oil a year for a 3,300-k.v.a. unit. The forced-cooled type of transformer has therefore one objection which should be very carefully looked into. I should like to know if it is the custom in water-cooled transformers to maintain the pressure of water less than the pressure of the surrounding oil, and how this can be done, if not by some system of suction. With regard to relative prices of three-phase and single-phase transformers,

three single-phase self-cooled units would be about 2½ per cent higher in cost than one water-cooled three-phase. In comparing the cost of installing a number of single-phase and three-phase units of corresponding capacity, the cost of connections is in my opinion one of great importance. A spare three-phase unit would be installed complete with its switchgear and protective gear, so that if one three-phase unit goes down, one has simply to switch in the spare. It can be used at any time, allowing frequent cleaning and inspection of the other transformers, etc., which this paper very rightly advises. A spare single-phase unit could not be installed in this way, as it has to be available for use with a number of sets of three, and would have to be connected up by a system of linkage or loose cables. It is therefore, although cheaper, nothing like as useful. The question of rating of transformers is important, particularly with colliery work, as, if our working days are to be made shorter than at present, say reduced to 6 hours, all our transformer loadings will have to go up correspondingly. Our load factor is at present pretty bad; if we go down to a 6-hour day it will be still worse. The load factor taken in comparing costs and ratios of copper and iron losses, namely, 70 per cent, is very high; we get more like 25 to 30 per cent. It is a very interesting figure from the point of view of substations, but hardly comparative for work such as we experience in this district.

Mr. F. S. Carter: I was very interested to hear the authors' remarks about handling transformers when filled with oil. To handle transformers underground when the cases are filled with oil would be a very difficult matter, owing to the confined space one has to work in and the small headroom. Even when handled on the surface where there is plenty of headroom and where suitable lifting appliances can be used, I should have thought the strength of the case would have been against lifting them complete. Owing to the great difficulty in getting transformer cases oil-tight, I should have also thought that to lift them complete, including the oil, would have strained the cases and caused oil leakages. I have not had experience with large transformers such as are referred to in the paper. The largest I have so far used underground are groups of three 120-k.v.a. single-phase transformers in separate cases, coupled up in delta and reducing from 3,000 volts three-phase to 550 volts. These I have had specially designed to reduce their height to suit the confined headroom met with in underground conditions. The largest transformers I have on the surface are a group of three 200-k.v.a. single-phase coupled in delta, and reducing from 3,000 to 550 volts. I am about to install a number of groups consisting of three 1,000-k.v.a. single-phase transformers in separate cases, coupled in delta/delta to step up from 3,000 to 11,000 volts and also to step down from 11,000 to 3,000 volts, for use in connection with overhead transmission lines. These transformers are insulated so that they can be coupled in star/delta later, to raise the voltage to about 19,000 and likewise reduce from that voltage to 3,000 volts. On the question of using three single-phase versus one three-phase transformer, I am inclined to favour the three single-phase transformers in separate cases, coupled in delta for the better maintenance of the supply. That is the system I have adopted.

Mr. C. G. Morley New: Whilst many comparisons are given in the paper, I see none in regard to the type of connection which may be used. The authors referred to the linking-up scheme between Manchester and Salford, and the desirability of standardization, with which I quite agree; it could be carried much farther with transformers. I think the authors said they had been connected with the scheme, and some further information would be useful. There may be some special reason why the transformers at one end are delta-star connected and the other end delta-delta; also at one end two three-phase 3,000-k.v.a. units are employed and, at the other end, a single-phase bank of 5,000 k.v.a. It may be that the phase relationship existing between the stations due to other linking-up settled the first point and, regarding the other, the connections for the single-phase units followed as a matter of extra security if the main factor was merit of single-phase versus three-phase units. In any case it seems a bad start towards standardization in what the authors state is the first 33,000-volt linking-up in this country. With reference to iron and copper losses of transformers I think it is a pity the comparisons which are carried out to some extent in detail were not qualified in the paper. In practice, substation transformers get moved about, which means that if a substation is cut fine as regards capacity, and if in the case of a breakdown it becomes necessary to put in a transformer of a different make, with a different proportion of copper and iron losses, parallel running is upset and it is necessary to put in larger k.v.a. capacity to meet the conditions. Makers do not seem inclined to give specific guarantees on this point, even for their own design of transformer. I think there is room for standardization in regard to the ratio of these particular losses, and I may say that in inquiries which I have dealt with, except for transformers required for purely residential districts, often used singly in circuit summer and winter where iron losses are specified to be a minimum, makers' standards are usually called for. I was interested in the reference to transformers for rotary converters. I think it was only in recent years it was found that commutation was affected by the design of transformer. I have in mind a set which is not as good as it might be in this respect, and I should like to know whether the reactance on an existing transformer could be altered without having to modify the spacing of the coils and taking the whole transformer apart. The notes under the heading "Operation and Care of Transformer Installations" are very practical and useful. I would, however, ask the authors to see that core-clamping bolts can be tightened up without having to remove the transformer out of its case. I have had experience where this was necessary on account of the bolts turning. At the end of the paper it is stated "It must also be borne in mind, especially under present conditions, that the attraction of higher efficiency may be obtained at a sacrifice of reliability and durability." I think a reason might be given for this statement.

Mr. A. C. McWhirter: I should like to know what

provision the authors make for allowing the leads connecting the low-tension side of transformers to take up their new position due to shrinkage of windings. I have experienced serious trouble from the settling of windings of the pancake type where the low- and high-tension windings were sandwiched. This was on a core-type transformer and actually caused an open circuit on the low-tension winding. The method of clamping windings is a very serious problem, especially in the core type, and I congratulate the authors on their dash-pot method to overcome this difficulty, and it would be interesting to know how this acts in actual practice. Personally, I should like to see the coils kept under pressure by a coarse-pitch screw, which could be operated by a clock-type spring under tension. This would prevent any movement of windings due to heavy surges. From a repair point of view there can be no doubt that the core type is much the simpler, and coils can be removed and replaced in a very much shorter time than would be required by the shell type. On the other hand, I believe the shell type will run much cooler owing to the coils being vertical, allowing the natural circulation of the oil and also preventing sludge gathering on the windings. I have seen core-type transformers with pancake coils practically filled solid with sediment between the windings, which must necessarily cause a great increase in temperature within the windings.

Mr. J. Wayne Morgan : In the past I have had considerable trouble with regard to oil, and, if larger transformers are to come into use, the question of oil should receive very special consideration.

Mr. A. G. Ellis (*in reply*) : I am glad to see the standpoint taken by Mr. Arthur Ellis as to the relations between the buyers and suppliers of electrical machinery and apparatus. It is always best for buyers to specify what they want to achieve and leave it to the manufacturers to put forward what, in view of their own experience and that of their various customers, they know will best meet the requirements. The designer is often hampered by conditions in a specification which, although well intentioned, really result in producing a less reliable piece of apparatus than would be the case if only the end to be achieved were specified and not the means of arriving at it. In connection with the point raised by Mr. Ellis as to crane-capacity limitation, it is quite apparent that money should not be stinted on the crane at the sacrifice of getting the best plant. We should have qualified our remarks by referring to existing central stations where the matter of extensions has to be considered involving the putting in of a unit many times the size of the unit for which the station was originally laid down. He also criticized our figure of spare plant, namely, one single-phase transformer for every six installed. This is perhaps on the liberal side, but the comparison for three-phase is on the same basis, and we intended to err on the side of reliability. There is a tendency for electrical designers to forget the practical end of the job—i.e. the mechanical, or reliability question—in reckoning primarily with electrical considerations. After a good many years' experience, both on the Continent and in this country, I am of opinion that the paramount factor is reliability of supply. It is of no use to turn out a piece of apparatus which is not absolutely efficient and which will not stand up to the job for more than a year or two. I am very glad to note that Mr. Ellis supports the adoption of the British Standard Rating, because we hope soon to have international rules which practically correspond to the present British Standard Rules governing electrical machinery. On the question of switching in, also raised by Mr. Ellis, we must be guided by the experience of the people actually doing this every day. I gather that the point of criticism was as regards damage to switch contacts. Our remarks on this point, which are governed to some extent by theoretical considerations, should perhaps have been qualified. Regarding the pooling of designs, that is a thing we should like to see done, and there are movements in this direction in the electrical manufacturing world even to the extent of combination of Continental and British firms. Whatever may be said against such combinations, they certainly have the advantage that the purchaser will have the best technical experience from practically all countries. Speaking as a designer, I should like to see that occur, because all electrical machinery is practically alike, and it is only in matters of small detail that machines differ. The British Engineering Standards Association might ultimately do a good deal in the direction of pooling designs and manufacturing experience.

With regard to Mr. Ellis's remarks on the question of periodicity and Mr. Chamen's reply, I should like to say that the paper was not intended to raise the periodicity controversy; we gave the comparative figures for alternative periodicities simply to show the facts of the case as a guide for people who are responsible for laying down power schemes and extending existing ones. As Mr. Chamen said, the periodicity question as such is not really relevant to the present discussion. A static frequency changer, such as Mr. Chamen referred to, is a piece of apparatus much sought after. As far as I know, only one invention exists, covered by a patent of which I cannot remember particulars of date and number. It is a three-phase core-type transformer with three legs and a neutral leg. The core is run at very high saturation to obtain a third harmonic flux in the neutral leg. This produces a secondary frequency in a winding placed on the neutral leg, of three times the primary frequency. The efficiency of the apparatus is necessarily very low, but the idea is there in principle as a possible basis for a static frequency changer.

Mr. Chamen asked, quite rightly, if the spring adjusting device for following up the shrinkage of coils in transformers had been tested in practice. A number of these transformers such as were illustrated on the screen have been running on a very large installation and, as far as I know, no trouble has been experienced with them. It certainly seems better to have a spring to follow up the shrinkage than to keep on tightening by hand, or to risk short-circuit through neglect to do so. As regards the dash-pot attachment, this is an innovation. There are many under construction, but none actually in service.* Good results are, however, hoped for.

* Since the date of this discussion a number of transformers built to this design have been put into service with satisfactory results.

Mr. Newman asked about variation of prices of transformers since the date the paper was written. Prices have certainly gone up due to increases in cost of labour and material. The main object of the curves is to show, however, that they are comparative, while being approximately correct for rough estimates in getting out schemes. Regarding road transport, I do not think there is much advantage, if any, over rail transport. We attempted to transport some heavy machinery from Manchester to Sheffield on a 5-ton lorry some time ago. The lorry turned over and killed three men. I think, however, the engineering limiting factor in regard to road transport is the bridges, very few of which are built to carry as much as 20 to 30 tons. A member of the Institution, when discussing this paper at Newcastle, suggested that the solution of the transport difficulty was by making use of the airship.

With regard to drying out transformers on site, it is true that they absorb moisture even after being dried out at the works. It depends entirely, however, on how long they are *en route* and standing about, as to whether drying out on site is necessary. If they are installed within a day or two of their arrival, after having been dried out at the maker's works and transported in oil expeditiously, it should be quite safe to put the transformers into service without further drying, thus avoiding considerable trouble and expense. The question of weatherproof transformers is not touched upon in the paper, and might almost form the subject of a separate paper. At present not much is done in England with regard to them except in small units, but in America they are built up to 100,000 volts and used to a large extent.

Regarding condensed latent-heat vaporization of water for cooling, a patent has, I believe, been taken out, but there are no practical results from it yet.

On the question of hot spots and relative cooling merits of the shell-type and core-type transformers, I consider the cooling to be rather better in the shell type by reason of the vertical ducts through which the oil can flow, giving generally better oil circulation. In the core-type windings, if one can wind the coils as single-layer coils and of very thin depth, one can achieve the same result, but it is not always possible to adopt this design of coil.

Mr. Newman criticized the annual charges for copper and iron losses. It seemed to us that all losses that go through a substation are charged up at the same rate, because the losses, as such, can have very little effect on the load factor of the substation. If the premises of the paper are not clear they should of course be qualified, but I think the point of view that the copper and iron losses have very little effect on the load factor of the whole substation is right. Mr. Newman also suggested that shrinkage of the windings reduces the safety factor. That is certainly so. It is dangerous not to follow it up. It was the necessity for doing this that led manufacturers to devise springs to take up the shrinkage of insulation automatically, or rather these devices have really, in effect, been demanded from the buying end. My experience is that the hand-screw adjustment for insulation shrinkage was very seldom tightened during service, only, in fact, when the transformer might be under inspection or when it had broken down—probably due to the neglect in hand tightening.

I am very glad that Major David remarked that the weight curves (Fig. 4) turned upwards at the higher ratings. It may seem a remarkable thing, but it is the fact that in self-cooled transformers beyond 5,000 k.v.a. the weight per kilovolt-ampere actually increases with the rating. The reason is, that in cooling such a large piece of apparatus the weight of the tank and also the volume of oil increase at a very rapid rate. This is practically where we reach the reasonable limit for self-cooled transformers. With regard to the 33,000-volt transmission line in South Wales, referred to by Major David, I was under the impression that the Manchester–Salford 33,000-volt interlinking was the highest voltage in use in this country, and that the line referred to by Major David was designed for 33,000 volts, but was meanwhile working at 20,000 volts. [**Major David :** That is so.] It is very interesting to hear that voltage regulators are considered unnecessary. A few years ago, when interlinking was being considered, it was laid down that there must be voltage regulators to adjust power factor. Major David's reference to losses of oil in forced-cooled transformers is very surprising. Even taken as a percentage of the total oil used, the oil losses he mentioned are more serious than anything I have previously heard of. I should be inclined to attribute them to defective workmanship in the cooler, probably in the tube joints, although these coolers are supposed to be tested under severe pressure. Keeping the oil pressure up in a forced cooled installation is a necessity to ensure that any leakage in the coolers is not a leakage of water into the oil. The prices stated by Major David for 2,000-k.v.a. tranformers correspond fairly well to the curves given in the paper. Major David also referred to the question of three-phase versus single-phase installations. Most of the discussion on that point shows that opinions differ considerably, and the question is, in the end, governed largely by local conditions. The attractive feature of the three-phase transformers with a spare is that the spare can be put in readily. But for small installations one cannot always afford to adopt this course. With, say, 2,000 k.v.a. installed, to have two 1,000-k.v.a. sets and one 1,000-k.v.a. spare is an expensive proposition. To reduce the percentage of spares it would be necessary to put in, say, four 500-k.v.a. three-phase transformers with one 500 k.v.a. as spare. This was the point in making the analysis in the paper, and it led to the conclusion that in small substations one is better off with single-phase sets, and in larger ones with three-phase sets. The connections do not present a serious problem. With a group of three single-phase transformers, one can easily make a star connection with the spare and then proceed as though one had a three-phase transformer. To replace one of the group when a breakdown occurs is sometimes a none too easy matter.

Mr. Carter spoke of transformers for colliery work below the surface. There are several designs of transformers of particularly robust construction intended for working below the surface, and they are practically oil-tight, so that it would be quite safe to fill them

on the surface and take them down without risk of oil splashing and leaking.

Mr. New referred to the type of connections. This is a very big subject and has been dealt with in several papers before the American Institute of Electrical Engineers. To deal with it adequately would be impossible in the present discussion. With regard to the Manchester–Salford interlinking, it may appear curious that one end of the line has a group of three single-phase 5,000-k.v.a. transformers and the other end 3,000-k.v.a. three-phase transformers. The single-phase group carries one spare. The reason that the Manchester end has three-phase transformers is that the Manchester end is a bigger system and three-phase 3,000-k.v.a. transformers may be a standard size there in appreciable numbers. Regarding the actual connections in the Manchester–Salford interlinking, delta/delta was, I believe, put in at the Salford end for facility of taking one transformer out in case of necessity and running the remaining two temporarily connected in open delta; and star/delta connections were chosen for the other end, as these were the standard connections for the system. On the question of parallel running, I was rather surprised to hear Mr. New say that he could not get the manufacturers to guarantee that his transformers would run in parallel. I always understood it was usual to guarantee that any transformer of one make will run in parallel with a transformer of any other make, subject to restrictions as to proper division of load, and makers will generally undertake that transformers of their own manufacture will run in parallel where the ratio of rated output is anything up to 5 : 1. That is to say, 100 k.v.a. will parallel with 500 k.v.a. but not with 1,000 k.v.a., which is of course reasonable. The present tendency is for standards of various transformer manufacturers to merge in regard to reactance recommended and general performance, and I think it will be found without doubt that different makes do approximate to one another in these respects. The main difficulty in parallel operation is where new transformers have to be fitted in with old ones. Probably the old ones have a low percentage reactance compared with the new ones, thus giving an unsatisfactory job, suggesting the necessity of scrapping the old ones or putting in reactances in series with the old transformers. With regard to high-reactance transformers for rotary converters, I am afraid that to increase the reactance on an existing transformer of this type would involve pulling it to pieces and altering or reconstructing it.

Mr. New criticizes the sentence at the end of the paper: "It must also be borne in mind, especially under present conditions, that the attraction of high efficiency may be obtained at a sacrifice of reliability and durability." That sentence may not have conveyed exactly what was intended, but what is meant is that if high efficiency is specified for a transformer, it can be obtained by cutting the insulation down, and it is of this practice we wish to register our disapproval. It is unsound practice to attempt to get an extra 0·1 per cent or 0·2 per cent efficiency by cutting the insulation down and turning out a much less reliable job.

Mr. McWhirter referred to the question of leads between coils and terminals where arrangements are made for following up the shrinkage of coils. We have generally allowed for that, in high-tension windings, by putting in a piece of flexible connection between the porcelain terminal and the top of the coil. In low-tension coils the question hardly arises, because low-tension windings generally have few turns, with a big mass of copper, so that the percentage of the length liable to shrinkage is only about 15 per cent.

On the question of butt-jointed yokes in core-type transformers, to lift the yoke off to get at the coils would appear to be an easy matter, but it generally has other disabilities. The special construction increases the iron losses in the core by about 15 per cent. With interleaved (lap) joints with the punchings sandwiched together, the pulling out and putting together is not as formidable as it would appear to be, for the reason that nowadays the punchings are put up in packets of several plates together, so that one can take hold of the plates in each packet and pull them out together, reducing the labour and time considerably below what what was necessary to handle them singly.

I agree with Mr. Wayne Morgan that the question of oil is a very important one, and a special paper before the Institution dealing with transformer and switch oil would be very useful at the present time.

DISCUSSION ON "ALTERNATING-CURRENT TRACK CIRCUITING."*

Mr. M. R. Gardner (*communicated*): I should like to congratulate the author on the extremely lucid manner in which he has dealt with a somewhat complex subject. The vector diagrams enable one to see at a glance what is happening in each part of a track circuit and also to view it clearly as a whole. They also show very clearly the progress that has been made in recent years, and emphasize the great improvements obtainable by the use of resonated impedance bonds and two-element vane relays. Until a few years ago, double-rail alternating-current track circuits were usually equipped with ordinary impedance bonds and single-element vane relays. Although the operating current of these relays averaged about 4 amperes, the total current consumption of such a track circuit, about 1,000 ft. long and under good conditions of ballast resistance, averaged about 16 amperes with the track clear, due to the low impedance of the ordinary impedance bonds. Fig. 13 shows that, by the use of resonated impedance bonds and a two-element vane relay, it is possible to reduce the total consumption to 0·91 ampere with the track clear. This is a most marked improvement as, besides reducing the operating costs and the necessary sizes of track connections, etc., it gives the important advantage of enabling higher track-shunt values to be obtained. The high current consumption and low shunt value of alternating-current tracks in the past has acted as a deterrent to their adoption in situations where they would otherwise be of benefit. On electrified lines using the running rails for the traction current they are, of course, necessary. On other lines, both steam and electric, they are very desirable, and as their energy consumption is lowered and their track shunt value raised they will doubtless be more widely used. With reference to single-rail track circuits, the author has described a method of preventing the track relay from being rendered inoperative by the direct current flowing in the parallel path shown in Fig. 30. When a short-circuit occurs on a train, or on the traction current rails, the direct current in the parallel path may become excessive. In general, due to the operation of circuit-breakers, this excess persists for a very short interval of time and has no deleterious effect on the track relay other than causing it momentarily to release. Where, however, the track feed resistance consists of thermal regulators, these are apt to be burnt out, thus putting the track circuit out of operation. This will result in a signal failure on the "safe" side, but it will cause traffic delays. A coil of high impedance and low resistance connected across the track rails at the feed end of the track circuit will prevent this trouble to some extent, but will have the disadvantage of increasing the normal current consumption of the track circuit and altering its power factor. The case cited above, though an abnormal one, is unfortunately by no means rare, and when it does occur causes considerable delay. This difficulty does not arise with double-rail track circuits equipped with impedance bonds. Were it feasible to introduce a condenser into the track feed, the direct current could be entirely eliminated from the transformer, but, with the track voltages and currents at present in use, the capacity of such a condenser would make it prohibitive. As, however, traction short-circuits have always to be reckoned with, I should be interested to learn what the author considers the best means of overcoming this difficulty. In Fig. 27 the author showed a method of feeding the track circuit through a capacity and inductance in series. This enables a reduction to be obtained in the amount of current taken by the track when it is shunted, and also gives a change of phase angle to a poorer relay-operating value. Both these methods result in a higher track shunt value being obtainable, which is of distinct advantage. The latter method of feeding will, of course, give no protection against the direct-current trouble referred to above, as the capacity and inductance are connected in the primary of the track transformer. Judging from the progress that has been made in the last few years I consider that the future before alternating-current track circuiting is most encouraging and that this paper will prove to be a valuable addition to the literature on the subject.

Mr. L. H. Peter (*in reply, communicated*): Mr. Gardner has referred to the use of impedance coils connected across the feed transformer as a means of protecting thermal regulators during periods of direct-current short-circuits. This method is referred to on page 504 of the paper. These impedance coils afford protection at the feed end, but tend to pass an additional direct current which must also be carried by, or shunted past, the relay, hence it may be necessary to provide impedance coils both at the feed end and at the relay end of the track circuit. If this method of protecting against direct-current short-circuits is adopted, the shunting-out point of the track circuit is materially lowered. The author prefers the other method mentioned on page 504, namely, keeping the resistance of the alternative direct-current path formed by the feed resistance, transformer winding, section rail and relay, high enough to prevent excessive direct current through the regulating resistance. A few years ago this method was practically impossible, as the comparatively heavy currents required by the alternating-current relays then in use would have necessitated a large regulating resistance and a very high watt dissipation in the track feed case. Nowadays, the small current required for, say, the two-element vane relay allows a high ohmic resistance to be inserted in the track feed without causing high watt dissipation, and this high ohmic resistance affords all protection necessary against traction short-circuits.

* Paper by Mr. L. H. Peter (see page 491).

DISCUSSION ON

"A PRACTICAL METHOD OF HARMONIC ANALYSIS."*

Mr. A. E. Clayton (*communicated*): The study of the wave-shapes occurring in alternating-current work is of such great importance, that any attempt to improve the methods of the analysis of such wave-forms is to be welcomed. Mr. Kemp's paper is, in addition, of interest as it emphasizes the fact that any mathematical method of harmonic analysis based upon a limited number of selected ordinates, such as the original Perry method, or its simplification by Runge, or the adaptation of Runge's method to the case of odd harmonics only, as set forward by Thompson, does not give correct results under certain conditions. In some respects, however, the paper is a little disappointing. To obtain the various multiplying factors, two sets of nine simultaneous equations, containing the various factors, are used involving, as one may well imagine, "considerable initial labour." This labour would appear to be unnecessary, as the constants are exactly those which would be used in the ordinary Perry method or any of its modifications, namely, one-ninth of sin 5°, of sin 15°, of sin 25°, etc., the ordinates being erected at 5°, 15°, 25°, etc. In fact, the chief point of difference that is apparent between the method of analysis put forward by the author and the Thompson method, would appear to lie in the fact that the ordinates are erected at these angles, instead of at 10°, 20°, 30°, etc. In certain cases it is true that by basing calculations upon the mid-ordinates more accurate results are obtained than by using the normal method; but it is equally true that in other cases the use of mid-ordinates will give rise to a greater error than the normal method. It is not possible to enter fully here † into the magnitude of the errors that are likely to arise in practice by the use of Thompson's method of analysis. It may be stated, however, that for the wave-shapes normally met with, the theoretical accuracy of the method is very much greater than the accuracy of the necessary measurements is likely to be, and that the average error, i.e. averaged over a number of waves of different form, will be much the same whether the mid-ordinate or the normal method is used. Taking as examples the three simple wave-forms represented respectively by:

(1) $e_1 = 100 \sin pt + 5 \sin 35\,pt - 5 \sin 37\,pt$;
(2) $e_2 = 100 \sin pt + 5 \sin 35\,pt - 5 \sin 71\,pt$;
(3) $e_3 = 100 \sin pt + 5 \sin 35\,pt + 5 \sin 71\,pt$.

For the first of these waves, when the half period is divided into 18 parts, an error of 10 per cent will occur in the value deduced for the amplitude of the fundamental for both the normal and the mid-ordinate methods. For the second wave, the value deduced for the amplitude of the fundamental is correct for the normal method, and has an error of 10 per cent for the mid-ordinate method. For the third wave, the mid-ordinate method gives correct results, and the normal method has an error of 10 per cent. Compared with the Thompson method, too, the use of mid-ordinates is in the nature of a retrograde step, since by using mid-ordinates it is no longer possible to group the "supplementary" harmonics (the 1st and 17th, 3rd and 15th, etc.), and the full number of multiplications has to be carried out for each individual harmonic. The author's choice of ordinates therefore, instead of reducing the labour involved in the harmonic analysis of wave-forms, considerably increases it over that necessary for Thompson's adaptation of Runge's method, since twice as many multiplications are required. In addition, for the analysis of pressure waves, waves normally containing only sine terms, the use of mid-ordinates really necessitates the division of the half period into twice as many parts as the number of ordinates utilized, in order that the ordinates may be correctly placed. This is a matter of some difficulty when 18 ordinates are used.

Mr. P. Kemp (*in reply, communicated*): The relative amount of labour involved in working out analyses by the method under discussion and by other methods is questioned by Mr. Clayton. The solving of the various simultaneous equations may be compared with the evaluation of a table of logarithms, both of which processes require "considerable initial labour." The schedule given in the paper enables a person to analyse a wave-form, just as a table of logarithms enables him to work out certain calculations, although he may not understand the process in either case. In other words, the actual work may be put out to a junior, so that the method may be considered to be a labour-saving device from the point of view of the engineer. I do not agree that the labour is increased in an actual evaluation, as groupings of ordinates would be employed in this method in the 3rd, 9th, and 15th harmonics, so that the full number of multiplications need not be carried out. With reference to the question of accuracy, it is true that a limit is imposed by the accuracy of the experimental observations, but surely increased accuracy in the analysis is not in itself a disadvantage. The examples chosen by Mr. Clayton are very severe tests, as a wave containing a 5 per cent 71st harmonic is a most extraordinary one, and considering that the constants used are only intended to analyse a wave up to the 17th harmonic, I think it is very good that the error should be as low as 10 per cent. The present method could, of course, be extended to include harmonics higher than the 17th by the aid of a larger number of ordinates and the use of a different set of constants. In this way the fundamental could be more accurately determined in the case of a wave showing pronounced higher harmonics.

* Paper by Mr. Kemp (see Supplement to vol. 57, page 85).

† I am contributing to the *Journal* (vol. 59) a short paper dealing with the accuracy of the Perry method, and also of its Runge and Thompson simplifications.

THE USE OF VACUUM TUBES FOR WIRELESS TRANSMISSION AND THE RECEPTION OF CONTINUOUS WAVES.

By JOHN SCOTT-TAGGART, Student.

(*Abstract of paper read before the* STUDENTS' SECTION, 10 *April*, 1920.)

The present paper is intended to cover briefly the use of vacuum tubes for the transmission and reception of continuous waves in wireless telegraphy. It is proposed to divide the subject into two parts:

(1) The use of vacuum tubes or valves in generating circuits.
(2) Some modern methods employed for receiving continuous-wave signals by using the heterodyne principle.

Actual working examples will be given and these will include several devices and circuits which the author has designed and, in some cases, patented.

VACUUM TUBE TRANSMISSION.

The subject of three-electrode vacuum tubes or triodes (a term suggested by Dr. W. H. Eccles) has been dealt with by Mr. R. L. Smith-Rose in a paper * read before the Students' Section, and it will therefore not be necessary here to treat of the now well-known principles of the vacuum valve except in so far as concerns the present branch of the science.

The three-electrode vacuum tube consists essentially of an evacuated bulb containing three electrodes, a cathode consisting of a filament heated to incandescence by means of a battery, an anode usually in the form of a metal plate surrounding the filament, and a grid which usually takes the form of a spiral of wire surrounding the filament and placed between the filament and plate. The incandescent filament emits electrons which may be drawn to the plate by applying a positive potential to the latter. This may be done by connecting a battery across the filament and plate. The resulting plate current may be varied by altering the potential of the grid with respect to the filament. A positive potential on the grid will cause a marked increase in the plate current, while a negative potential will cause the grid to repel electrons on their way to the anode, thus decreasing the plate current.

A three-electrode valve is capable of generating oscillations. A simple theoretical circuit is shown in Fig 1. Here we have a plate oscillatory circuit $L C_1$ coupled to a grid oscillatory circuit R. On switching on the filament current a rush of current flows through L and sets up oscillations in $L C_1$. Normally these oscillations would die out owing to the wastage of energy in the circuit. By coupling R to L, however, the magnified oscillations in R retroact on the original oscillations in L and maintain them by compensating for the energy losses in $L C_1$. The operation of the circuit is comparable with that of a swinging pendulum, which would normally come to rest. By giving the pendulum taps at the right moment, it is possible to overcome the losses due to friction and maintain the swing of the pendulum.

If the coupling between R and L is less than a critical value the vacuum tube will not oscillate of its own accord. Any oscillations momentarily set up in $L C_1$ will, however, die out much more slowly than if the phenomenon of retro-action were not employed.

Many modifications of the circuit are possible. The retro-actor coil R is shown aperiodic, but if desired a variable condenser might be connected across it.

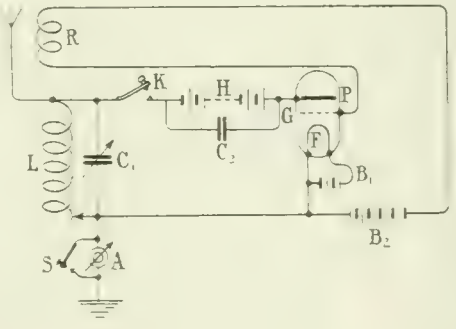

FIG. 1.

In the case of wireless transmission circuits it is customary to couple the plate oscillatory circuit, in which the main power is developed, directly or indirectly to the aerial. Frequently the capacity of the aerial replaces in part or in whole the condenser of the plate oscillatory circuit. In this case the grid oscillatory circuit is usually aperiodic, although a slight increase of efficiency is sometimes obtained by tuning this circuit with the aid of a condenser.

It is rather outside the scope of this paper to enter into the deeper theoretical studies of the oscillating valve, which subject has been expounded by various authors. It may be as well, however, to point out that a vacuum tube used for transmission should be operated at or near the midway point on the characteristic curve showing the relationship between plate current and grid potential.

Fig. 1 shows a typical circuit suitable for the trans-

* *Journal I.E.E.*, 1918, vol. 56, p. 253.

mission of continuous waves. The aerial and earth are connected directly to the plate oscillatory circuit $L C_1$ of the three-electrode vacuum tube. The inductance L, which may be varied by means of tappings, is connected in the direct-current plate circuit which has for its source of electromotive force a battery H of about 400 volts. Across H is connected a condenser C_2 which by-passes the oscillatory current in the plate circuit. A key K is connected in the plate circuit to enable Morse signalling to be effected. The retro-actor coil R is aperiodic and its coupling with respect to L is variable and is adjusted to give the maximum aerial current reading as indicated by a high-frequency ammeter A, which may be short-circuited by a switch S when not in use. An ordinary flash-lamp bulb may be used in place of the ammeter, the brightness of the filament giving a comparative indication of the aerial current.

Marconi's Wireless Telegraph Company have described * another vacuum tube generator, but in this case the vacuum tube has a grid in the form of a metal sheath outside the glass of the tube. In U.K. Patent 13248/14 the same inventors describe a continuous-wave generator used in a wireless telephone circuit.

Lee de Forest has patented a number of vacuum tube transmitters. A closed circuit is connected across the grid and plate of a three electrode vacuum tube, in the plate circuit of which is an impedance. Further de Forest circuits are described in U.K. Patent 107001, but as they are not used in this country it is not proposed to describe them here.

We have so far chiefly discussed vacuum tube generators in which the retro-action is obtained by magnetically coupling the grid and plate oscillatory circuits. Retro-action is, however, obtainable by utilizing capacitative coupling. The grid and plate oscillatory circuit are coupled by means of a condenser which should be variable. The maximum energy generated may be varied by altering the value of the coupling condenser, which will also modify the frequency of the oscillations. Such a circuit is not always very stable and it is preferable to couple the inductances magnetically to obtain additional retro-action and to steady the operation of the circuits.

In the circuits so far discussed the plate battery has been connected in series with the plate oscillatory circuit. This arrangement is not essential; we may, if desired, keep the direct plate-current circuit quite distinct from the oscillatory circuit by connecting the two in parallel.

Production of High Voltages for Transmission Circuits.

The provision of a source of high voltage for applying the necessary position potential to the plate of the transmitting tube is a problem in itself. Batteries consisting of a large number of dry cells connected in series are only suitable for small-power transmission and become very cumbersome and expensive when potentials higher than 400 volts are required. The high-voltage problem has been solved in a number of ways which come under the following headings:—

(1) Direct-current dynamos or motor-generators.
(2) Induction coils and the use of positive half-cycles of alternating current.
(3) Use of half-wave rectifiers in conjunction with induction coils.
(4) Use of half-wave rectifiers in conjunction with step-up transformers supplied with alternating current.
(5) Use of full-wave rectifiers of alternating current.
(6) Use of both half-cycles of alternating current without rectification.

Direct-current dynamos.—These have been frequently used where an alternating-current supply is not obtainable. A direct-current dynamo giving about 150 milliamperes at 400 volts has been extensively used on aeroplane wireless sets where power is easily obtained by means of a small driving propeller. For portable ground stations where power is not easily or conveniently obtained, motor-generator sets are most often used, the source of low-voltage current for the motor being accumulators.

Use of induction coils.—For portable small-power sets an induction coil is a suitable source of high E.M.F. The voltage obtained is of a semi-alternating nature, the half-cycle at the "break" being of greater amplitude than that at the "make." The secondary terminals are connected to the terminals to which the plate battery would normally be connected. The connections to the secondary should be such that the half-cycle produced at the "break" makes the plate of the vacuum tube positive with respect to the filament. While the plate is positive a number of continuous oscillations take place in the circuits and are radiated from the aerial in the form of waves. When the following half-cycle makes the plate negative no current flows in the plate circuit and consequently no oscillations are generated. The waves radiated from a set of this description are no longer continuous but are divided into groups of continuous waves having a train frequency equal to the frequency of the semi-alternating current supplied by the induction coil. The waves differ from the ordinary damped waves emitted from spark stations, not in group frequency, but in the number of oscillations in each group. Groups of damped waves usually contain about 20 cycles, whereas those we are concerned with may contain as many as 300.

We thus see that the waves from such a station can be received on an ordinary non-oscillating wireless receiver as used in the reception of undamped waves. The best results are, however, obtained when the circuits used are of the heterodyne type discussed in the second part of this paper. The note heard resembles that of a spark station and to a certain extent the notes obtained when receiving continuous waves. The greater the frequency of the interrupter the higher will be the notes heard at the receiving station. In order to produce a clear musical note at the receiving station, the frequency of the interrupter should be such as to give a wave group frequency of about 1,000. To obtain such a frequency a rotary "make and break" is desirable,

* U.K. Patent 13247/14.

and a Wilson induction coil has been found very useful in practice.

Half-wave rectifiers.—The numerous disadvantages of the semi-continuous wave or tonic train system are obvious and some means of obtaining a high-voltage direct current is required. Generators are usually unsuitable for supplying high-voltage direct current of low amperage although some very useful generators have been recently designed for moderate power. Consequently, most high-power vacuum-tube transmitters obtain their plate current from a rectifier unit. This, in its simplest form, consists of a Fleming valve. The valve conducts when the anode is made positive, but when the anode is made negative by the succeeding half-cycle no current whatever flows in the circuit. To overcome the intermittent effect, we connect a large condenser across the load.

A high-power transmitting circuit which has been used with success is shown in Fig. 2. In this circuit the filament of the rectifying bulb (V_2) is heated by alternating current taken from the secondary (T_4) of a step-down transformer (T_3 T_4) fed from the mains.

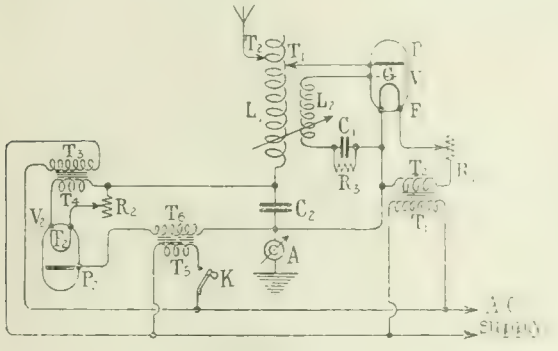

FIG. 2

Across the alternating-current mains is also connected the primary (T_5) of a step-up transformer (T_5 T_6). A key K is included in this circuit for signalling purposes. The high voltages across T_6, which may range from 1,000 volts to 10,000 volts according to the power of the set, are rectified by V_2 and charge up the condenser C_2 which acts as the source of high potential in the plate circuit of the transmitting tube (V_1). A separate aerial circuit might be used if desired, in which case the inductance in the aerial circuit would be coupled to L_1. In Fig. 2 the filament of the transmitting tube is shown heated by alternating current. A leaky grid condenser (C_1) is used to obtain a suitable operating potential on the grid and to lessen the grid current. It is to be noted that the reservoir condenser (C_2) is connected in the position shown. This arrangement ensures the filament of the rectifier being insulated from the earth without the use of a separate condenser.

A special half-wave rectifying vacuum tube.—The author has designed a special valve for use as a high-power rectifier.* In the ordinary rectifying tube the anode usually consists of a cylinder of metal surrounding the filament. During operation, the electrons on their way to the anode constitute a negative space-charge which tends to neutralize the effect of the positive potential on the distant anode. The result of this is a great reduction in the anode current which can only be remedied, and then only partially, by using very high anode potentials which are inconvenient to generate. The effect of the space-charge is more marked the greater the diameter of the anode. The present author has devised a means of neutralizing the space-charge, thus allowing lower anode potentials to be used and also permitting the use of an anode of greater diameter, which is capable of a greater dissipation of heat.

The anodes used by the author have a portion of their metalwork constructed close to the filament and between the filament and the main cylindrical anode. The portion thus arranged is of an open-work nature so as largely to neutralize the negative space-charge, while allowing the majority of the electrons to pass through the spaces to the main portion of the anode. One form of anode is made by attaching a spiral grid-like structure within the anode. During operation, the inner spiral is of course at the same potential as that of the main portion of the anode. Consequently, the space-charge is neutralized and full advantage is taken of the emission from the filament, thus resulting in a higher efficiency. Heavy currents at low plate voltages are obtainable by means of this valve.

Full-wave rectification.—Although half-wave rectification is largely used in the production of high-voltage direct current, yet it will be clearly seen that only one half of each cycle is utilized. Both half-cycles may be used if we employ two separate vacuum-tube rectifiers so arranged that alternate half-cycles operate the valves in turn.

A special full-wave rectifying tube.—The author has designed and made a number of varying kinds of full-wave rectifying tubes (described in U.K. Patent 146708). In a typical example, instead of two valves, only one is used, thus lessening the cost while gaining several advantages such as uniformity of vacuum. The device consists essentially of a filament passing through the centres of two substantially cylindrical anodes. The alternating voltage makes the anodes alternately positive and negative with respect to the filament. Consequently, the electron current flows alternately to the anodes, while flowing unidirectionally in the external circuit.

Use of alternating current without rectification.—Above we have seen how rectified high-voltage alternating current may be employed in continuous-wave transmission. By using two three-electrode vacuum tubes we can, however, accomplish the same result without a separate rectifying system. In this case each vacuum tube acts as a generator in turn. It will be seen that practically continuous waves will be radiated from the aerial when the key is depressed. A tonic-train note will, however, usually be heard if the receiver is within a few miles of the transmitter. The waves are not so perfectly undamped as in the case of transmitters using rectifiers.

A transmitting tube for use with alternating current.—The author has devised,* constructed and used a special form of vacuum tube which is capable of generating continuous oscillations by the direct application of

* British Patent 154,364.

* U.K. Patent 146708.

high-voltage alternating current. It consists essentially of a single filament passing through the centres of two substantially cylindrical anodes, a common grid (preferably of spiral form) being situated between the filament and anodes.

Methods of keying.—The method of transmitting the continuous waves in the form of Morse signals is a problem in itself. It is usual, in small-power sets, to include a tapping-key in the plate circuit. When the plate current is large this method is not very convenient as the contacts are liable to arc. Sometimes the key is included in the grid circuit. Although the arcing trouble is eliminated, yet, even when the key is released, there is still a dissipation of energy due to the steady plate current. This steadily applied energy is very liable to heat up the plate of the transmitting tube to red or almost white heat.

Another method of keying consists in applying a large negative potential to the grid when not transmitting. On depressing the key, this potential is removed. Another arrangement consists in including a key between the negative side of the plate battery and the filament. The grid circuit is connected to the filament through the key. This arrangement reduces arcing to a minimum.

An obvious method of signalling which wastes no energy is to include a key in the filament circuit. This can only be done in the case of very slow signalling and is very damaging to the filament.

Another method is to arrange for the key to detune the aerial when not depressed. Although the aerial is radiating all the time yet it is only doing so on the normal communicating wave-length when the key is depressed. This system, which has been applied to arc transmitters, is not to be favoured.

A method of signalling which has been used in practice consists in arranging a low-power oscillating circuit with its output circuit coupled to the input circuit of a high-power amplifying vacuum tube. The current through the small tube or " master oscillator " may be easily controlled by the key. Several tubes may be thus connected in series for high-power transmission. The grid of the power amplifier is given a negative potential.

The Reception of Continuous Waves.

The use of a crystal detector for the reception of continuous-wave signals is obviously unsuitable. The result, for example, of a dash would be a steady flow of rectified current which would produce no buzz in the telephone receivers. It is, consequently, necessary to interrupt either the continuous waves or the rectified current in order to produce the required note in the telephones. The obvious way to receive continuous-wave signals in the form of a buzz is to cut up the steady flow of oscillations into groups at the receiving station. Each of these groups will then be rectified and will give a click in the receivers, the dash being heard as a buzz. The question now arises how to cut up the continuous waves into groups. We could of course connect a very rapid make-and-break in the telephone circuit or the aerial circuit. We should, however, clearly lose about half the energy received, since in between the groups the oscillations would be wasted. Another arrangement would be to connect an interrupter in the telephone circuit. The advent of the oscillating valve has, however, revolutionized our methods of receiving continuous waves.

To understand the action of what is known as beat reception, we have to consider the interference effect produced by two sets of alternations or oscillations in a given circuit. If the two sets of oscillations are of equal frequency, the result will take the form of an oscillating current having a frequency equal to the original frequencies and an amplitude which will vary between the sum of the two amplitudes and the difference between them, according to the phase relationship. When, however, the frequencies of the original sets of oscillations differ, the resultant current is oscillatory, but rises to a maximum and decreases to a minimum at regular intervals. The explanation of this is that the two sets of oscillations are at one point assisting each other, and at another opposing each other. The points of maximum amplitude are known as beats, the amplitude of these beats equalling the sum of the individual amplitudes of the original oscillations.

It will be readily seen that by causing a local source of continuous oscillations to be induced into a circuit receiving continuous waves from an external source, we can produce beats in the receiving circuit having a frequency which may be adjusted to any value by varying the local frequency. The problem so far has been the provision of a convenient source of local oscillations. The use of the three-electrode valve as a generator has, however, solved this problem. The wave-length of the oscillations produced by the local oscillator is made to differ slightly from the incoming frequency. Beats are produced which are rectified by a detector, producing an audible signal in the telephones. Each beat will produce a click in the telephones and if there are several beats to, say, a dash, a buzz will be heard. The human ear, however, cannot detect, and telephones will not respond to, frequencies lower than about 100 and higher than about 14,000; consequently, it is necessary to arrange the local frequency so that the frequency of the beats falls between these limits. The most suitable beat frequency is in the neighbourhood of 1,000. It will be seen that the local frequency may be either above or below the frequency of the incoming oscillations. When the local frequency equals the incoming frequency no beat note will be heard.

Obviously a three-electrode valve may be arranged as a detector in place of the crystal. The disadvantage of this arrangement is that two valves are necessary. The system of beat reception, or heterodyne reception as it is sometimes called, may, however, be utilized by making the receiving valve act as an oscillator as well as a detector.

Fig. 3 shows a simple and effective continuous-wave receiver. The coil (R) is aperiodic and is coupled to L_1 sufficiently tightly to cause the valve to oscillate of its own accord at a frequency which can be varied by the condenser (C_1) and the adjustable tapping on the inductance (L_1). This frequency is made, as usual, a little different from the incoming frequency. A leaky

grid condenser causes the valve to act as a detector. This circuit is exceedingly simple to tune. To "pick up" a station, it is only necessary to vary the condenser C_1 and sometimes the inductance L_1. The frequency of the aerial circuit is varied at the same time as the frequency of the local oscillations, consequently the aerial circuit is always a little out of tune when continuous-wave signals are heard. As the condenser C_1 is moved round, the incoming signals are first heard as a high note which is rather faint. The frequency at which the valve is now oscillating differs from the incoming frequency by about 10,000. When the condenser is turned round still further, the signals become louder and their pitch becomes lower until the point is reached when no sound is heard. The local frequency at this adjustment is equal to the incoming frequency; the aerial circuit is now correctly in tune with the incoming waves. If we gradually turn the condenser round still

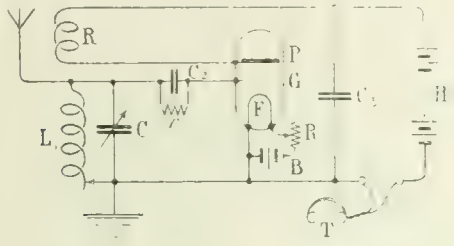

FIG. 3.

further, signals re-appear and gradually acquire a higher note again, which finally dies out.

Since the vacuum tube is oscillating continuously, it is obviously emitting feeble waves which are radiated from the aerial. These oscillations are weak, but they are quite sufficient frequently to carry a distance of several miles. The receiving circuit is clearly acting as a very weak transmitter and as such it will cause very considerable interference to neighbouring receiving stations. Two stations in the same town using circuits of the self-heterodyne type will cause endless trouble to each other by overhearing each other's valve oscillating. Self-heterodyne circuits are consequently not to be encouraged, and the use of a local oscillator is strongly to be recommended. In any case, such an oscillator is almost an essential part of every wireless receiving station and has very many applications. Even with an external oscillator, however, a certain amount of radiation from the aerial is possible although this is negligible compared with the amount produced by circuits of the type shown in Fig. 3. The radiation from the aerial may be lessened by using a loosely coupled circuit.* Here we also obtain a greater selectivity on account of loose coupling between the aerial and closed circuit inductances. These inductances may be several feet apart, if desired.

The author has used a system for receiving continuous waves, which he has described in a paper before the Wireless Society of London. The arrangement is reproduced in Fig. 4, and full details will be found in the original paper. Two principal methods of employing the circuit are as follows: With S over to the left, the circuit B is adjusted to amplify retro-actively the incoming continuous waves. The oscillations are then received on the self-oscillating A circuit. Loudest results are obtained if the switch (S) is now moved over

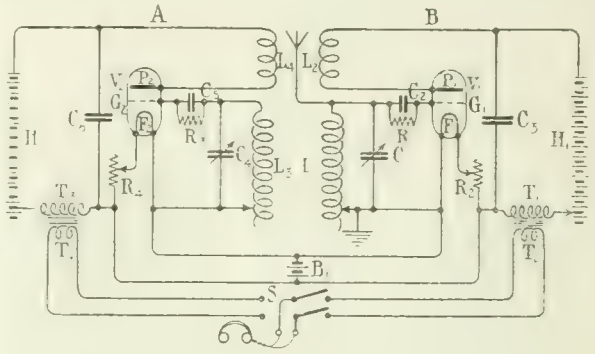

FIG. 4.

to the right. With this arrangement the circuit (B) is accurately tuned to the incoming frequency and there is no loss of strength as in the case of self-heterodyne circuits.

Another type of continuous-wave receiving circuit of practical value has recently been described by the author in the *Electrical Review*.†

All the above types of continuous-wave receiving circuits may, of course, be varied in a variety of ways. For example, several valves may be added to produce low-frequency magnification. Also the continuous waves may be amplified by several valves before being heterodyned and detected. Innumerable circuits have been and are being designed and it is outside the scope of the present paper to include any but a few of the more well-known circuits and the one or two for which the present author has been responsible. The 27 circuits which have been given are fairly representative of modern practice.

* The author has described in British Patent 153,681 a special valve which receives continuous waves without radiating.

† *Electrical Review*, 1919, vol. [illegible], p. [illegible].

PROCEEDINGS OF THE INSTITUTION.

9TH WIRELESS SECTIONAL MEETING, 9 JUNE, 1920.

(Held at the Institution of Mechanical Engineers.)

Dr. W. H. ECCLES, Chairman of the Wireless Sectional Meetings Committee, took the chair at 6 p.m.

The minutes of the Wireless Sectional Meeting of the 17th March, 1920, were taken as read, and were confirmed and signed.

A paper by M. Marius Latour entitled "High Frequency Machines" was read and discussed, and the meeting adjourned at 7.45 p.m.

651ST ORDINARY MEETING, 16 JUNE 1920.

(Held at the Institution of Mechanical Engineers.)

Mr. ROGER T. SMITH, President, took the chair at 6 p.m.

The minutes of the Annual General Meeting of the 20th May, 1920, were taken as read, and were confirmed and signed.

An introductory paper by Sir Dugald Clerk, entitled "Note on the Thermal Efficiency of the Generation and Use of Gas and Electricity" (see page 765), was read, and a discussion took place on the following :—

(1) The paper read by Sir Dugald Clerk before the Royal Society of Arts, entitled "Distribution of Heat, Light, and Motive Power by Gas and Electricity";

(2) The Report of the Coal Gas and Electrical Supply Industries of the United Kingdom to the President of the Institution of Gas Engineers," by Sir Dugald Clerk, K.B.E., D.Sc., F.R.S., Prof. Arthur Smithells, C.M.G., F.R.S., and Prof. J. W. Cobb, C.B.E., B.Sc., F.I.C.

The meeting adjourned at 7.55 p.m.

10TH WIRELESS SECTIONAL MEETING, 23 JUNE, 1920.

(Held at the Institution of Mechanical Engineers.)

Dr. W. H. ECCLES, Chairman of the Wireless Sectional Meetings Committee, took the chair at 6 p.m.

The minutes of the Wireless Sectional Meeting of the 9th June, 1920, were taken as read, and were confirmed and signed.

A paper by Mr. B. S. Gossling, entitled "The Development of Thermionic Valves for Naval Purposes" (see page 670), was read and discussed, and the meeting adjourned at 7.40 p.m.

652ND ORDINARY MEETING, 30 JUNE, 1920.

(Held at the Institution of Mechanical Engineers.)

Mr. ROGER T. SMITH, President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting of the 16th June, 1920, were taken as read, and were confirmed and signed.

A paper by Sir Philip Dawson, Member, entitled "Electric Railway Contact Systems" (see page 838), was read and discussed, and the meeting adjourned at 7.50 p.m.

OBITUARY NOTICES.

JOÃS NEPOMUCENO BAPTISTA died on the 31st May, 1918. He was born on the 15th August, 1849, at Rio de Janeiro and passed through the Naval School, afterwards entering the Polytechnic School in the same city, where he completed his studies in Natural Science. He obtained, by examination, the post of teacher in Physics at the Naval School, and later became Professor of Electricity there. For two years he was also Director-General of Telegraphs in Brazil. He wrote and published several monographs, and a book on "Capillarity." He was elected a Foreign Member of the Institution in 1890 and a Member in 1911. He was also a member of the Polytechnic Institute of Brazil.

HENRY SMITH CARHART was born in Coeyman, New York, on the 27th March, 1844, and studied at Wesleyan University (Middleton, Conn.), where he obtained the degree of B.A. in 1869, of M.A. in 1872, and of LL.D. in 1883. He also studied at Yale University in 1871, at Harvard in 1876, and at Berlin in 1881–1882, where he was in the laboratory of von Helmholtz. During the years 1872–1886 he was Professor of Physics in North-western University, Evanston, Illinois, and from 1886 to 1909 he held a similar position in the University of Michigan, becoming Emeritus Professor of Physics in the last-mentioned year. He was a member of the International Jury of Awards at the Paris Exposition of Electricity in 1881, President of the Board of Judges in the department of electricity at the Columbian Exposition in Chicago in 1893, a member of the Jury of Awards at the Buffalo Exposition in 1901, and one of the delegates of the United States to the International Electrical Congress at Chicago in 1893 and at St. Louis in 1904. In 1901 he was the delegate of the American Institute of Electrical Engineers to the International Engineering Congress in Glasgow. He was also a delegate to the Conferences on Electrical Units and Standards at Berlin in 1905 and at London in 1908. In 1905 he also attended the South African meeting of the British Association, and in 1909 represented the University of Michigan at the centennial celebration of the birth of Charles Darwin at Cambridge. In 1889 he was vice-president of Section B of the American Association for the Advancement of Science, and later served as vice-president and as president of the American Electrochemical Society. His principal subjects of research were: Standard cells, the thermodynamics of the voltaic cell, the separation of iron losses in transformers, the rotation of the magnetic field, concentration cells, and the absolute determination of the electromotive force of the Clark and cadmium standard cells. In addition to over 50 scientific papers he was the author of a series of well-known textbooks. He first became known to the scientific world in 1881 by reason of his experimental work on voltaic cells, a subject on which in later years he was a world authority, and he was one of the pioneers of electrochemistry in the United States. After retiring from the active duties of his profession he made his home in Pasadena, California, where in 1912 he accepted the honorary position of Research Associate in Physics in the California Institute of Technology. He died on the 12th February, 1920. A faithful student, he was also an inspiring teacher and an enthusiastic investigator. He was elected a Foreign Member of the Institution in 1894 and became a Member in 1911. E. S. C.

CAPTAIN ETTRICK WILLIAM CREAK, R.N., C.B., F.R.S., was born on the 28th May, 1835, being the son of the late Commander William Creak, R.N., and a nephew of Sir H. Havelock of Lucknow fame. He joined the Navy at the age of 14, and served on board H.M.S. "Esk" from 1863 to 1867 on the Australian station. The great range of magnetic latitude traversed during the commission turned Lieutenant Creak's attention to an investigation of the errors of the compass arising from that cause. This was the beginning of his researches in the science of magnetism, and led to his appointment as an Assistant in the Compass Department of the Admiralty in 1868. In connection with the famous "Challenger" Expedition of 1872–6 he took an active part in the determination and control of the constants required for the reduction of the magnetic observations to be made during the voyage. To him was entrusted the instruction of officers engaged in the Arctic Expedition of 1875, and the preparation of the directions and magnetic charts for the Arctic Manual. He also drew up the Magnetic Instructions for the Antarctic Expedition of 1901. For some years before Commander Creak's appointment as Superintendent of the Compass Department in 1887 the necessity for a compass better suited to modern ships than the existing Admiralty standard had been recognized. Sir William Thomson (Lord Kelvin) had already introduced his well-known compass, fulfilling all requirements except the one essential to ships of war, namely, ability to withstand the shock of heavy gun-fire in large ships and the effect of vibration and rapid motion in small vessels such as torpedo boats and destroyers. Captain Creak was confident that the solution of the problem lay in the development of the liquid compass and set himself to attain that object. The existing liquid compasses were far from being reliable instruments. The cards were floatless, with large moments of inertia and the weight resting upon the pivot was excessive, necessitating powerful needles with large magnetic moments in order to overcome the sluggishness resulting from the inertia, skin friction of the liquid, and the friction between the cap and pivot. He introduced cards mounted on a float, with two thin and relatively

short needles fitted with their poles at the scientifically correct angular distances, and with the centre of gravity, centre of buoyancy and the point of suspension in correct relation to each other. The flotation and the total weight were so adjusted to one another as to reduce the weight resting on the pivot to a reasonable amount, and at the same time sufficient to prevent the card from jumping when subjected to vertical shocks or vibration. He was thus able to use iridium-pointed pivots instead of the relatively blunt ruby-pointed pivots which had hitherto been used. An improved form of azimuth circle was introduced at the same time. The compass thus designed rectified the defect of the Admiralty standard compass with the additional advantage of considerable steadiness under heavy gun-fire and in a seaway.

Notwithstanding this great improvement, as a manœuvring compass it was inferior to Lord Kelvin's, owing to comparative sluggishness on a large alteration of course, through the drag on the card by the liquid in which it floated, and solely on that account, in 1892, the Admiralty adopted the Kelvin compass for the use of the Fleet. Some years later, Messrs. E. Dent & Co. constructed a liquid compass for use by submarines, with a slightly reduced diameter of card and projecting lubber point. It was at once observed that this small alteration removed the sluggishness hitherto noticeable and rendered the instrument equal to the Kelvin compass for manœuvring purposes, whilst retaining its superiority in other respects. The triumph of the liquid compass was now therefore complete, and in 1908 it was adopted for general use in the Navy under the name of the "Chetwynd compass." For his various contributions to Magnetism, Captain Creak was elected a Fellow of the Royal Society in 1885, and served on the Council from 1898 to 1900. From time to time papers were read by him at the Royal Society on subjects connected with magnetism on board H.M. ships, and the discussion of the results of magnetic observations made in the course of voyages by H.M. surveying vessels and scientific expeditions. A simple form of instrument for the correction of heeling error by magnets and the determination of vertical force both afloat and ashore was devised by Captain Creak, and he also invented the Lloyd-Creak dip and intensity apparatus. He was the author of the article on "Compasses" in the tenth edition of the "Encyclopædia Britannica," and other publications. Shortly before his retirement from the Compass Department in 1901 the honour of C.B. was conferred upon him. In 1903, in his Presidential address to the Geographical Section of the British Association, he gave an interesting account of our knowledge of magnetism both afloat and ashore up to that date. He was the most modest and unselfish of men, a staunch friend and full of charity to all. High minded, straightforward and true to the core, he died in his sleep on the 3rd April, 1920, in his eighty-fifth year, regretted by all who knew him. He was elected a Member of the Institution in 1890.

A. M. F.

CHARLES MARK DORMAN, who died at Llandudno on the 12th February, 1920, after a short illness, was one of the pioneers of the electrical engineering industry. Born at Northampton in 1861, he was educated at Berkhampstead and the Yorkshire College, and afterwards served an apprenticeship in the works and drawing office of the Hunslet Engine Company. In 1881 he and his subsequent partner, Mr. R. A. Smith, deserted locomotive engineering and joined the late Mr. J. S. Raworth as his assistants. Mr. Dorman carried out some of the earliest electrical installations on board ship, and was responsible for many of the early designs of switchgear and other electrical apparatus. When Mr. Raworth left Manchester, Mr. Dorman and Mr. Smith took over the small works which he had established and gradually developed the business which is at the present time carried on as Dorman and Smith, Ltd. Mr. Dorman was of a very studious nature and a great lover of science. His disposition was genial and hospitable, and he will be much missed. He was associated with the Manchester Astronomical Society, the Sale Photographic Society, the Wireless Telegraphic Society, and the Salford Education Committee. He manifested keen interest in the War Savings movement, and did much useful committee work. He took an active part in the formation and foundation of the Northern Society of Electrical Engineers, and was Chairman in the second year of the Society's existence, before it was merged in the Institution. He was elected an Associate of the Institution in 1884 and a Member in 1890.

JOHN EDGAR EDMUNDSON was born on the 22nd April, 1879, at Foxrock, Co. Dublin. His father who at that time was engineer to Messrs. Edmundson of Dublin, a firm then largely engaged in the construction of lighthouses, shortly afterwards moved to Gateshead and was engaged in the manufacture of incandescent electric lamps, first with the Ediswan Company and later with the Sunbeam Lamp Company. He was educated at the High School at Gateshead, and afterwards at the Friends' Boarding School at Ackworth, in Yorkshire. In December 1894 he started to serve his time with Messrs. J. Wigham, Richardson & Co., in their marine engine works at Newcastle, but left two years later and went to the Electrical Department of Messrs. Clarke, Chapman at Gateshead, being chiefly engaged on ship installation work. While living in Newcastle he attended lectures and classes at Armstrong College. In 1901 he was appointed assistant engineer at the electricity works, Brechin, one of the group of undertakings controlled by Messrs. Edmundsons' Electricity Corporation, and all his later work was in connection with this firm. His next appointments were on the construction of tramways between Camborne and Redruth, and in Glossop and Scarborough. He remained at the last-named town as engineer and manager until 1906, when he was appointed resident engineer and manager of the electricity supply undertaking at Grantham. During the time of his management at Grantham the undertaking was very considerably enlarged, and in 1914 and 1915 large contracts were carried out for the equipment and supply of the camp adjoining the town. In 1919 he was transferred to the more important undertaking at

Hawick. The output of these works during his management increased materially, and further plant was being installed at the time of his decease. His life was uneventful, but full of hard and enthusiastic work in the interest of his employers and of the undertakings with the management of which he was entrusted. He had a great facility for making friends, as he had a cheery and bright manner which made it easy for him to get into intimate touch with people in all walks of life. The letters which were written after his death by his brother engineers and the men who worked under him are a fine record of the influence which a man of absolute integrity and uprightness of character has on those with whom he associates. He was a sound engineer and a most executive manager. He died at the early age of 41, leaving a wife and four children, and his death was a loss to the firm for whom he had worked for 19 years. He was elected an Associate of the Institution in 1902, an Associate Member in 1905, and a Member in 1920. J. C. W.

JOHN STEEL NICHOLSON, O.B.E., D.Sc., Wh.Sch., was born at Alford, Aberdeenshire, on 21st December, 1879. He received his early education at Alford and subsequently at Robert Gordon's College, Aberdeen. From there he proceeded to the Glasgow and West of Scotland Technical College (now The Royal Technical College), and gained the diploma of the College and the Sir John Pender Memorial Scholarship. He entered the engineering classes at Glasgow University in 1898 and graduated B.Sc. after a distinguished university career, during which he gained many prizes, including the first Walker prize and the George Harvey prize. His apprenticeship in engineering was served on the "sandwich" system and in the summer of 1896 he commenced his practical work with Messrs. Matthew Paul & Co., Ltd., Dumbarton, completing his apprenticeship with them in 1901. From 1901 to 1904 he was a demonstrator under Professor Barr at Glasgow University and assisted in the development of the newly opened James Watt Laboratories. At that time also, he taught classes in Dumbarton Academy and Coatbridge Technical School and Mining College. In 1903 he gained first place in the Whitworth Scholarship examination. Then followed a year of special study and practical work in Germany, and in 1905 he was appointed, by Glasgow University Court, Lecturer in Electrical Engineering and chief laboratory assistant to Professor Barr. During this time he collaborated with Sir J. B. Henderson in research work on armature reaction in alternators, and with Professor Barr on the influence of temperature, loading, etc., on the elastic limit and the breaking stress of mild steel. On the outbreak of the War he joined the Officers' Training Corps and later took up munition work with Messrs. Denny & Company, Dumbarton. Shortly afterwards he was asked to join the Royal Flying Corps as an Equipment Officer. He continued at this work until demobilization in the autumn of 1919. He became a Section Director of the Aeronautical Supply Department with the rank of Major and was subsequently transferred to the Technical Department of the Air Ministry, and his services were recognized by the award of the O.B.E. Dr. Nicholson made many contributions to scientific engineering, and among them it might be noted his papers to the Institution on "A Simple Graphical Construction for determining the Efficiency of a Polyphase Asynchronous Motor from the Current (Circle) Diagram" and "A Single-phase Motor with Pole-changing Windings"; and his paper to the Institution of Engineers and Shipbuilders in Scotland on "Development of Metal Construction in Aircraft." In 1919 he was contemplating an extension of his paper on "The Magnetization of Iron at High Flux Density with Alternating Currents" read before the Institution in 1915. In May 1920 he was stricken with illness and in July it was decided to operate. He died on the 21st July after an illness borne with cheerfulness and hopefulness and when he was on the threshold of an important and useful career. All who knew Dr. Nicholson admired his manliness and tenacity, loved his unfailing cheerfulness and amiability, and respected him for his clearness and inspiration as a teacher and his accuracy as an investigator. His students, his colleagues, and his friends miss him. He joined the Institution as an Associate Member in 1906 and was transferred to full membership in 1917. He served on the Glasgow Local Centre Committee from 1906 to 1909, and on the Committee of the Scottish Local Section from 1913 to 1916. From 1907 to 1913 he was Vice-Chairman of the Glasgow Students' Section. J. D. C.

JOHN PERRY, M.E., D.Sc., LL.D., F.R.S., died in London on the 4th August, 1920. Every electrical, in fact every engineer, must mourn the death of Perry; but as he was a Past President of the Institution, and personally known to most of us, his loss touches us deeply. He was born in 1850, in Belfast; and he had practical engineering experience, and was also a keen student. He gained a Whitworth Exhibition which enabled him to get college training. He was appointed Physics Master at Clifton in 1870. It was here I first saw him. I remember the first time I heard him lecture, and his luminous treatment of mass and gravity, which put into words the reason why a heavy stone could be thrown higher against air and gravity than an empty ball—a point one never could explain in words as a child, though understanding the matter in the sort of way a dumb animal may grasp things. His lectures fired all the boys who had any scientific leaning with tremendous enthusiasm. Tilden came as Chemistry Master a few years later; and with the same power of inspiring the students. Perry was very young, about 21, and had some difficulty in preserving order. Once he had a mouse to illustrate something in electrostatics; but the discharge of a Leyden jar killed it before its experiment was due. The whole "set" immediately gave vent to howls and groans of "Cruel Mr. Perry!" "Who killed the mouse?" while Perry kept trying to explain that he never meant to hurt it. Boys used to ask leave to go out: they would play fives for ten minutes or so, and come back. One day the applications were too numerous even for Perry; so he snapped out: "You may not. You should go out before you come in." It is said that once, to save time,

he said : " I will not call all the names over ; all absentees hold up their hands."

After Clifton, Perry went to Sir W. Thomson in Glasgow, and thence to Japan. There he and Ayrton did a tremendous amount of work, mostly electrical. Many years afterwards I was telling him a story about Captain Cardew, who sat with Major Marindin, holding an inquiry about 1889. I had given evidence that Ferranti's Deptford cables must have a leakage capacity current of about an ampere ; and this was what was disturbing the Post Office telephones. Cardew asked me to see him after the hearing, and said : " I do not get quite the same result ; how did you make your calculation ? " I said the calculation was quite simple ; what result did Cardew get ? He admitted it was not " quite the same as mine." I found Cardew had forgotten v^2, the ratio of the electrostatic and electromagnetic capacities ; and his leakage current was 900 million billion amperes. Perry looked sad and said : " Why do you tell me that story ? Ayrton and I made the same mistake in Japan, and Maxwell never let us hear the end of it."

There is so much of interest in Perry's life that it will be best to concentrate on his influence on electrical engineering, more especially as other aspects of his work have been fully treated in various notices that have already appeared. As a teacher at Finsbury, and in South Kensington, his ability in clear explanation and his personal enthusiasm and influence can best be measured by the extraordinary success of City and Guilds students in the profession, many of them owing a great deal to Professor Perry.

As inventors, Ayrton and Perry were very active from about 1880 to 1885 or 1890. Of the partners it is clear Perry was the chief inventor. I do not remember whether Perry or Thomson invented the ohm-meter. The voltmeters and amperemeters with permanent magnets and specially shaped pole-pieces were very useful in the early eighties. From a modern point of view they were very poor ; but there was nothing better to be had then. The twisted-strip instruments followed. The idea was most ingenious and very original. Certainly the instruments absorbed so much power that when dealing with low pressures, or small currents, it was better to use the voltmeter to measure current, and the amperemeter for low pressures. All the same they were most valuable, and much needed. The most important inventions were motor and clock meters. These were long before their time. Ayrton and Perry's pendulum instrument was the original of modern clock meters ; and it was designed to measure ampere-hours, or watt-hours. The motor meter was the ancestor of those now in use. If a contact switch for cutting cells in and out of a battery makes contact with two blocks, it short-circuits one cell ; if it leaves one contact before touching the other, the circuit is broken. Perry invented the pilot contact with a resistance. On the other hand, Ayrton and Perry were the chief upholders of the fallacy that the design of a motor should be quite different from that of a dynamo. It was not until Mordey published an article in the *Philosophical Magazine* that this heresy was killed. For the last 30 years Perry did little in the way of inventing, though recently he turned his attention to the improvement of the gyrostatic compass. He was an expert in the theory of spinning tops. Probably the way a top always moves at right angles to the direction one wants it to go, appealed to him as an Irishman. About 1890 he had a collection of tops arranged to illustrate, somehow, Maxwell's electromagnetic theory of light ; and his " Spinning Tops " is a delightful work.

Professor Perry was always an active member of the Institution, of which he was elected a Member in 1878, and in conjunction with Ayrton he read many papers ; also he often joined in discussions. He was President in 1900–1901. Personally he was a splendid, warm-hearted Irishman ; perfectly straight, and transparently honest. Ireland has given us more than her share of men with high mathematical powers and original minds. He was always genial, and full of humour ; and he never had, or could have an enemy in the world. He was a Whitworth Scholar (1870), F.R.S. (1885), also a D.Sc. and LL.D. His best-known books are " Steam " ; " Applied Mechanics " ; " The Steam Engine " ; " The Calculus for Engineers " ; and " Spinning Tops." He has also done yeoman work in the improvement of education, especially as regards mathematics.

J. S.

AUGUSTO RIGHI was born at Bologna on the 27th August, 1850, and was educated in that city. He was appointed, in 1871, assistant in the physics department of the University of Bologna, and two years later succeeded Paccinotti as head of the Physics Laboratory at the Bologna Technical Institute. Subsequently he became, in 1880, Professor at the University of Palermo, and in 1885 at Padua University. In 1899 he returned to his native city on being appointed Professor of Physics at Bologna University, a position which he held until his death on the 8th June, 1920. He was a member of numerous Italian Societies and of the principal foreign scientific Societies, and on three occasions was President of the Royal Academy of Sciences. He also served as President of the Italian Physical Society. He was considered to be Italy's leading physicist, and most of the scientific Societies of his country at various times awarded him important prizes, among others the King's Prize for Physics of the Accádemia dei Lincei. He also received in 1905 the Hughes Medal and Prize of the Royal Society of London, of which he was elected a Foreign Member in 1907. In recognition of his high scientific attainments the Italian Government in 1905 nominated him a Senator of the Italian Parliament. He was the author of numerous papers and works on magnetism, electricity, and light, several of which have been translated into other languages. Among the papers may be mentioned those on the subject of electric waves, previous to the development of wireless telegraphy. This work placed Righi in the front rank of pioneers in connection with conduction in gases. Among his more recent work may be mentioned his investigations on the conduction of gases in a magnetic field. His published works include " A Modern Theory of Physical Phenomena." He was elected an Honorary Member of the Institution in 1917.

FREDERICK WILLIAM SEDGWICK died at Roorkee on the 22nd March, 1920, at the comparatively early age of 50. His death caused a serious loss to the senior ranks of the Indian Educational Service in the United Provinces, India, where for 22 years he had held the post of Professor of Electrical Engineering at the Thomason Civil Engineering College. He was the only son of the late Lieut.-Colonel W. H. Sedgwick, and was born in Dublin. He received his early school education near Oxford and later at Trinity College, Dublin, and Emmanuel College, Cambridge, where he took mathematical honours. Subsequently he served an apprenticeship with a firm of electrical engineers and worked for a time on the staff at Seafield Park. In 1897 he was selected by the Secretary of State for India to fill the newly-created post of Professor of Electrical Engineering at the Engineering College at Roorkee, which was being re-organized at that time in accordance with the recommendations of the Colvin Committee. The Thomason College was really an Indian forerunner of Cooper's Hill founded about 1847. The great advances in engineering education which took place in England during the 'seventies and 'eighties rendered necessary some modification of the original purpose and scope of the College at Roorkee. Consequently, no light task confronted Professor Sedgwick on his arrival in India, and during the 22 years which he spent at Roorkee his energies were whole-heartedly devoted to the educational interests of the institution whose staff he had joined. Though not a strong man physically, he never spared himself where the interests of his work were concerned. His advent marked an epoch in the life of the college, at which he strove to lay the foundations of a modern school of engineering. His work was handicapped by difficulties incident to educational work in India, but that he achieved no small measure of success was clearly shown in an appreciative notice which accompanied the announcement of his untimely death in the *United Provinces Government Gazette*. He was a man of varied interests and considerable charm of social manner, which will cause his loss to be deeply regretted in a wide circle of acquaintances, pupils and colleagues. To his personal friends the circumstances of his very sudden end appeared especially tragic, since he died after a very brief illness within a few weeks of the date on which he was to have taken furlough to England, where his wife and children were awaiting his arrival. He was elected an Associate of the Institution in 1894 and a Member in 1911.

E. F. T.

SUGGESTION FOR BINDING VOLUME 58.

When "Institution Notes" are bound with the *Journal* they should be inserted immediately after page 904 and be followed by this Index.

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(P) indicates a reference to the general title or subject of a paper or address.
(p) indicates a reference to a subject dealt with in a paper or address of which the title is not quoted.
(D) indicates a reference to a discussion upon a paper or address of which the general title or subject is quoted.
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